Appl. Phys. B 46, 43–60 (1988)

Applied Physics B Photophysics and Laser Chemistry

Passive Q-Switching and Mode-Locking for the Generation of Nanosecond to Femtosecond Pulses

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Received 2 December 1987/Accepted 8 January 1988

Abstract. The passive and hybrid Q-switching and mode-locking of solid-state lasers, dye lasers, semiconductor lasers and gas lasers is reviewed. The dynamics of saturable absorbers and reverse saturable absorbers is illustrated. The nanosecond pulse generation by passive and hybrid Q-switching of low-gain active media is described. The picosecond and femtosecond pulse generation by passive and hybrid mode-locking in low-gain and high-gain active media is analysed. The performance data of passively and hybridly mode-locked cw femtosecond dye lasers are collected. The pulse shortening of ultra-fast pulses with saturable absorbers in intra-cavity and extra-cavity configurations is discussed.

PACS: 42.55

The photonic switching of lasers provides an important technique to generate short light pulses in the nanosecond to femtosecond time regime. The photons generated in the laser modify the transmission of the switching elements and cause the formation of short pulses. Saturable absorbers serve as intensity or energy dependent coupling elements in most cases. But occasionally intensity and energy-dependent refractive index changes have been applied.

Nanosecond light pulses are generated in passively Q-switched lasers. The passive mode-locking of laser leads to the generation of nanosecond, picosecond or femtosecond pulse trains. The actual pulse durations depend on the spectroscopic data of the active media and of the passive elements.

The nonlinear response of absorbers to light radiation is introduced in the next section [1–9]. The passive, and the hybrid Q-switching are discussed in Sect. 2 [10–12]. The passive, and the hybrid mode-locking are described in Sect. 3. A distinction is made between the mode-locking of low-gain [13–34] and high-gain active media [35–45]. The simultaneous Q-switching and mode-locking is discussed shortly in Sect. 4. A final section is devoted to the intra-cavity and extra-cavity pulse shortening with saturable absorbers [46–50].

1. Absorbers

The nonlinear absorbers may be dyes in liquids or solids, molecular gases, color centers, or semiconductors. The passage of a light pulse through a nonlinear absorber leads to a pulse shaping, as illustrated in Fig. 1a. The absorption dynamics may be discussed by a four-level system, as depicted in Fig. 1b. The incident photons excite molecules from the ground state 1 to an excited state 2 (ground-state bleaching). The excited molecules relax fastly to a temporal equilibrium position 3 of the excited state (τ_{FC} very short). From level 3 the molecules relax to the ground state with an absorption recovery time constant τ_A. During the stay of the molecules in levels 2 and 3 they may be excited to higher lying states 4 by absorption of incident radiation (excited-state absorption). The relaxation from level 4 to level 3 is generally very short ($\tau_{ex} \to 0$). Saturable absorbers [1–9] are characterized by $\sigma_A > \sigma_{ex}$ (Fig. 2a and b). For reverse saturable absor-

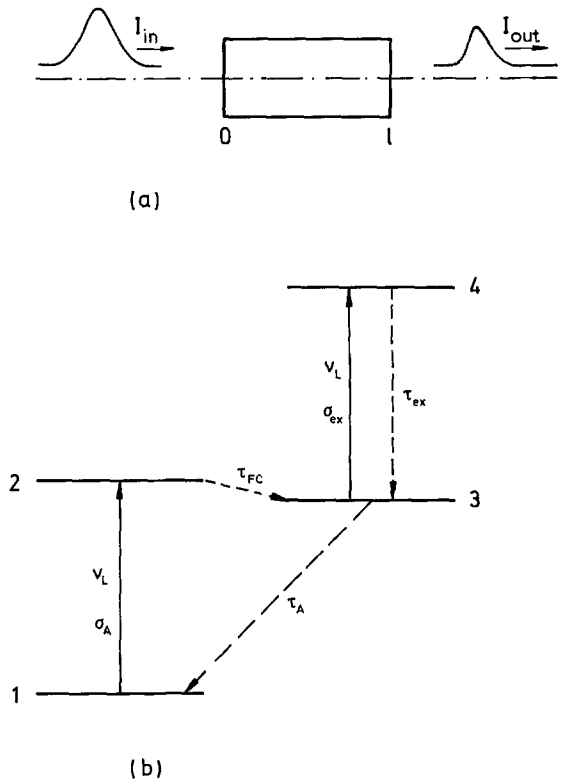

Fig. 1. (a) Passage of a light pulse through a saturable absorber. (b) Four-level system of absorbers (saturable absorber: $\sigma_A > \sigma_{ex}$; reverse saturable absorber: $\sigma_A < \sigma_{ex}$)

bers [1, 51–59] the excited-state absorption dominates, i.e. $\sigma_A < \sigma_{ex}$ (Figs. 2c and d).

Fast absorbers have a recovery time τ_A short compared to the laser pulse duration Δt_L and to the cavity round-trip time t_R of the lasers. The transmission through a fast absorber is given roughly by [8]

$$T = \frac{I_{out}}{I_{in}} \simeq \exp(-\sigma_A N_1 l - \sigma_{ex} N_3 l)$$
$$\simeq \exp\left(-\sigma_A \frac{N_0}{1 + I_{in}/I_S^A} l - \sigma_{ex} \frac{N_0}{1 + I_S^A/I_{in}} l\right). \quad (1)$$

N_0 is the total number density of absorber molecules. I_S^A is the saturation intensity. Its value is

$$I_S^A = \frac{h\nu_L}{\sigma_A \tau_A}. \quad (2)$$

Equation (2) is valid for $\tau_{FC} \ll \tau_A$ [2].

The nonlinear transmission and the pulse shaping of a fast saturable absorber are illustrated in Figs. 2a and a′ [48]. The leading and trailing part of the pulse are absorbed preferentially. The light pulses are shortened by the passage through the absorber cell. Fast saturable absorbers are applied mainly for mode-locking of low-gain lasers (solid-state lasers, CO_2 lasers, iodine lasers).

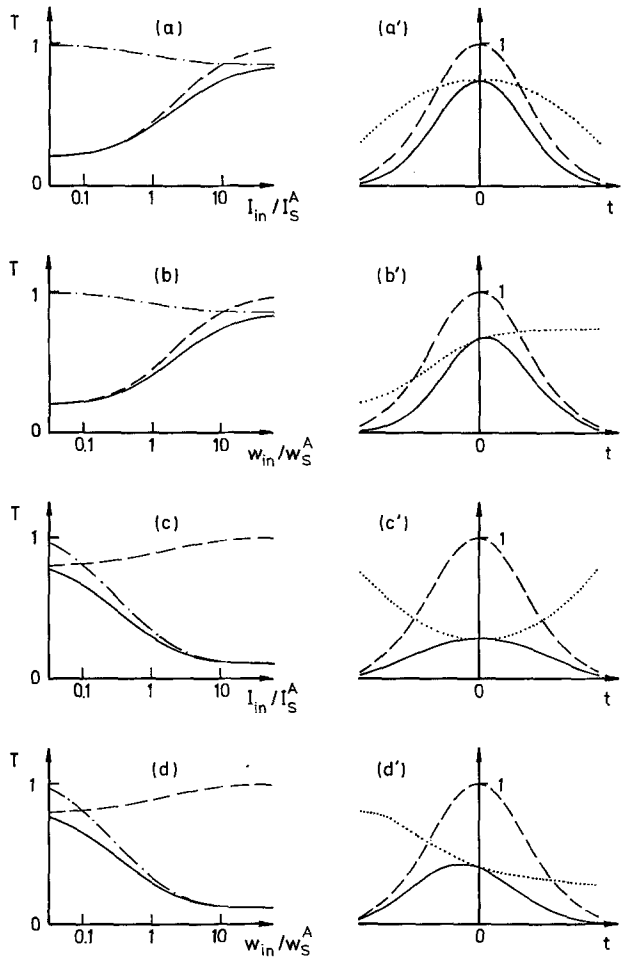

Fig. 2. Transmission behaviour and pulse shaping of absorbers. Left half: Nonlinear transmissions T. Dashed curves, ground-state absorption (transition 1–2); dash-dotted curves, excited-state absorption (transition 3–4); solid curves, total transmission. Right half: Dashed curves, normalized incident pulses $I_{in}(t)/I_{in,0}$; solid curves, transmitted pulses $I_{out}(t)/I_{in,0}$. Dotted curves represent temporal transmissions $T(t)$. $I_{in} = I_{in}(t)$; $I_{in,0} = I_{in}(0)$; $w_{in} = \int_{-\infty}^{t} I_{in}(t')dt'$; $w_{in,0} = \int_{-\infty}^{\infty} I_{in}(t')dt'$. (a) and (a′) Fast saturable absorber ($\sigma_{ex}/\sigma_A = 0.1$; $I_{in,0} = 10 \times I_S^A$). (b) and (b′) Slow saturable absorber ($\sigma_{ex}/\sigma_A = 0.1$; $w_{in,0} = 10 \times w_S^A$). (c) and (c′) Fast reverse saturable absorber ($\sigma_{ex}/\sigma_A = 10$; $I_{in,0} = I_S^A$). (d) and (d′) Slow reverse saturable absorber ($\sigma_{ex}/\sigma_A = 10$; $w_{in,0} = w_S^A$)

The transmission and the pulse shaping of a fast reverse saturable absorber are shown in Figs. 2c and c′. The input pulses are broadened in the absorber. Fast reverse saturable absorbers may be applied for power limiting [59].

Slow absorbers have a recovery time τ_A which is long compared to the laser pulse duration Δt_L. The light transmission through a slow absorber is approximately given by [8]

$$T \simeq \exp\left(-\sigma_A \frac{N_0}{1 + w_{in}/w_S^A} l - \sigma_{ex} \frac{N_0}{1 + w_S^A/w_{in}} l\right), \quad (3)$$

w_S^A being the saturation energy density [J/cm^2]. Its value is

$$w_S^A = \frac{h\nu_L}{\sigma_A}. \tag{4}$$

The transmission and pulse shaping behaviour of a slow saturable absorber are depicted in Figs. 2b and b'. The light pulses are shortened at the leading part. Slow saturable absorbers are suitable for passive Q-switching of lasers, and they are often used for passive mode-locking of high-gain lasers (dye lasers, color-center lasers, semiconductor lasers, excimer lasers, He–Ne lasers, Ar^+ lasers).

The transmission and pulse forming of slow reverse saturable absorbers are shown in Figs. 2d and d'. The absorption is increased in the trailing part of the pulses. For the depicted Gaussian input pulse shape the slow reverse saturable absorber broadens the output pulse somewhat ($\Delta t_{out} > \Delta t_{in}$). Input pulses of rectangular temporal shape would be shortened. The combined application of a saturable absorber and a slow reverse saturable absorber is thought to improve the pulse shortening [55, 57].

2. Passive Q-Switching

In Q-switched lasers the resonator losses are changed from high values (low-quality factor Q) to low values (high Q-value) after the pump pulse energy has been accumulated for a sufficient time in the active medium. The switching to a high Q-value brings the laser far above threshold. The resulting high net gain generates a steeply rising intense pulse. The end of the laser action is due to the depletion of the upper laser level [10–12, 60–63]. The steepness of the trailing edge of the generated pulse is determined by the photon-lifetime of the cavity, $\tau_{cav} \simeq t_R/\ln(R2)$ (trailing half width $\geqq$ round-trip time t_R, $R2$ is the reflectivity of output mirror M2) [63].

The storage time of the pump pulse energy in the active medium is limited by the upper laser level lifetime τ_G. Only low-gain active media have long upper laser level lifetimes and are suitable for Q-switched laser operation (ruby: $\tau_G \simeq 3$ ms; Nd:YAG: $\tau_G \simeq 250$ µs, Nd:glass: $\tau_G \simeq 350$ µs, alexandrite: $\tau_G \simeq 50$ µs [63], CO_2: $\tau \approx 1$ ms for $p \simeq 1$ mbar [61]). The energy storage capacity is limited approximately to the saturation energy density, $w_S^G = h\nu_L/\sigma_G$, by the onset of amplified spontaneous emission [63] (ruby:

$\sigma_G = 2.5 \times 10^{-20}$ cm^2, $\lambda_L = 694.3$ nm, $w_S^G = 11.4$ J/cm^2;

Nd:YAG:

$\sigma_G = 8.8 \times 10^{-19}$ cm^2, $\lambda_L = 1.064$ µm, $w_S^G = 0.21$ J/cm^2;

Nd:glass:

$\sigma_G \simeq 4 \times 10^{-20}$ cm^2, $\lambda_L = 1.055$ µm,

$w_S^G = 4.5$ J/cm^2;

alexandrite:

$\sigma_G = 7 \times 10^{-21}$ cm^2, $\lambda_L = 750$ nm, $w_S^G = 38$ J/cm^2).

High-gain active media (large σ_G, small τ_G) are not suitable for Q-switching. For these media cavity dumping is used to generate intense short pulses [64].

Passive Q-switching is achieved generally with saturable absorbers in the laser oscillator. Slow saturable absorbers are more convenient than fast saturable absorbers. Refractive-index changes may also be applied to Q-switching [65]. The passive Q-switching has been combined with active Q-switching (hybrid Q-switching) [66–68].

2.1. *Passive Q-Switching with Saturable Absorbers*

The schematic of a passively Q-switched laser is shown in Fig. 3a. The laser consists of the active medium, the saturable absorber and a frequency narrowing or tuning element. The Q-switch operation is explained by the Figs. 3b–e. The excitation pulse of pump rate J (Fig. 3b, dimension of photons cm^{-3} s^{-1}, or W cm^{-3}) populates the upper laser level (Fig. 3c). As soon as the upper laser level population N_u crosses the low-Q threshold population N_{th}^{LQ}, laser action sets in. If the intensity of the generated laser radiation approaches the saturation intensity of the absorber, the losses in the resonator are reduced, the laser-threshold population lowers to N_{th}^{HQ}, and strong amplification of the radiation occurs. The generated radiation depletes the upper laser level population rapidly and terminates the laser action. If the generated pulse is not intense enough to approach the absorber saturation intensity I_S^A, the laser remains at the low-Q threshold and a damped laser spiking occurs. Focusing of the laser radiation into the saturable absorber cell may be employed to achieve Q-switching.

For long pump pulses or continuous pumping a repetitive Q-switching occurs [69, 85]. The temporal spacing between the Q-switched pulses is shortened with rising pump power.

Slow saturable absorbers (τ_A in the *ns* region) have low saturation intensities and facilitate the Q-switching. Fast saturable absorbers in lasers with broad-band active media mode-lock the radiation. The mode-locking is suppressed by spectral narrowing the gain profile with resonance reflectors, Fabry-Perot etalons, birefringent filters, or gratings. The spectral gain narrowing elements may be used for laser frequency tuning within the gain profile of the active medium [70, 71].

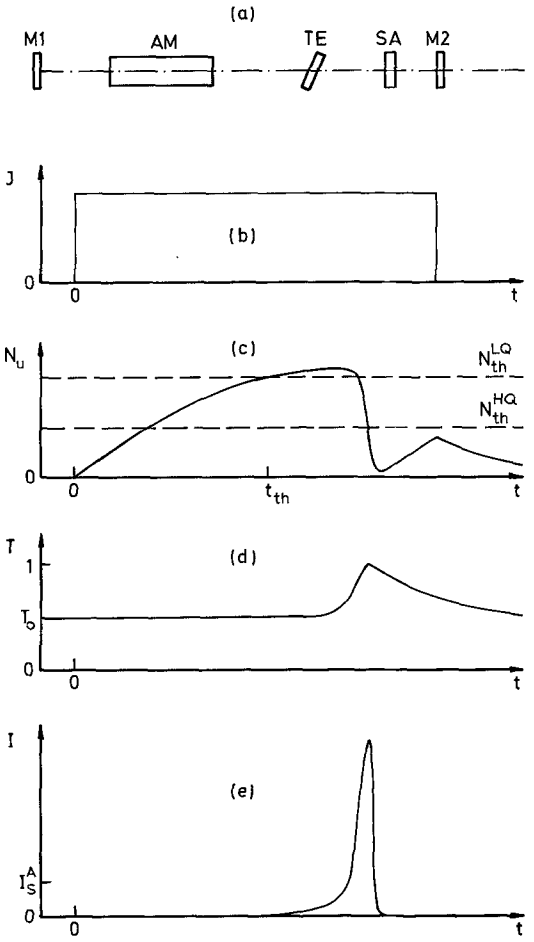

Fig. 3a–e. Passively Q-switched laser. (a) Schematic experimental setup. (M1, M2: laser mirrors, AM: active medium. TE: tunning element, SA: saturable absorber). (b) Temporal profile of excitation pulse J (dimension: photons/cm^3 s or W/cm^3). (c) Upper laser level population N_u (solid curve). The dashed curves indicate the low-Q (N_{th}^{LQ}) and high-Q (N_{th}^{HQ}) laser threshold population. (t_{th}: start of laser action). (d) Temporal transmission through saturable absorber. (T_0: small signal transmission). (e) Temporal pulse development. (I_S^A: saturation intensity of absorber)

Short-cavity resonators with low output-coupler reflectivities R2 and saturable absorbers with absorption recovery times less than the cavity round-trip time ($\tau_A < t_R$) allow the generation of short Q-switched pulses in the time domain around 1 ns [72, 73].

Since the first passive Q-switching of ruby lasers with organic dye solutions [74–76] various solid-state lasers (ruby, alexandrite, Nd:YAG, Nd:glass; pulse durations typical 10–20 ns) and CO_2 lasers (pulse duration between 400 ns and 2 µs) have been Q-switched with different saturable absorbers. References to the various Q-switched lasers are given in Table 1.

The passive Q-switching with saturable absorbers has to compete with active Q-switching [60–63]. The passive Q-switching is simpler and allows the generation of shorter pulses. The active Q-switching with electro-optic shutters has a better shot-to-shot stability and is easy to synchronize with other lasers.

2.2. *Hybrid* Q-*Switching*

The simultaneous active and passive Q-switching combines the advantages of active and passive Q-switching [66–68]. In [66 and 67] mechanical shutters and organic dyes have been applied to Q-switch ruby lasers. In [68] a hybridly Q-switched Nd:YAG laser has been described. A rotating roof prism is used for active Q-switching. The passive element is a F_2^- : LiF crystal. Multiple pulse generation is avoided by the mechanical switching. Pulses down to 10 ns duration have been obtained.

2.3. *Passive* Q-*Switching by Refractive Index Changes*

Besides the application of saturable absorbers for passive Q-switching, the intensity dependent refractive index changes may be employed for Q-switching. In [65] the self-focusing action of a Kerr liquid in an unstable Nd:glass laser reduces the diffraction losses and changes the configuration to a stable resonator. The loss-reduction causes the Q-switch pulse formation.

3. Passive Mode-Locking

Passive mode-locking instead of passive Q-switching occurs under the following conditions: i) the spectral gain width $\Delta\nu_G$ of the active medium is broad ($\Delta\nu_G \gg t_R^{-1}$, spontaneous emission signal is fluctuating within round-trip time [109]), ii) spectral gain narrowing is avoided, and iii) the saturable absorber recovery time is short compared to the round-trip time ($\tau_A < t_R$) [110, 111].

Fast saturable absorbers are needed for low-gain active media. The obtained pulse durations are of the order of the absorption recovery time. In a steady-state system the pulse duration is determined by the balance between pulse shortening (saturable absorber) and pulse broadening (finite spectral width of active medium, power limiting effects [59, 113]) [32, 112].

If $\tau_A \ll \Delta\nu_G^{-1} \leqq T_2^G$, ($T_2^G$ is the phase relaxation time of the active medium) then the coherent light-matter interaction determines the pulse development (π-pulse generation, self-induced transparency). For this situation pulses with durations Δt_L less than the inverse gain width $\Delta\nu_G^{-1}$ have been generated (ruby and Nd:YAG at low temperature) [114–116].

Table 1. Passively Q-switched lasers

Active medium	Absorber	Ref.
Ruby $\lambda_L = 694.3$ nm		
	Liquid organic dye solutions	[72, 74–86]
	Organic dyes in polymers	[79, 85]
	Semiconductor glasses (edge filters)	[78, 79, 87]
	Color centers in ruby	[85]
Alexandrite $\lambda_L = 730$–783 nm		
	Color center $((F_2^+)_A NaF : Li)$	[70]
Nd:YAG $\lambda_L = 1.064$ μm		
	Liquid organic dye solutions	[88–91]
	Organic dyes in polymers	[73, 92, 93]
	Color centers (F_2^- : LiF)	[68, 69, 94, 95]
Nd:Glass $\lambda_L \simeq 1.055$ μm		
	Liquid organic solutions	[89–91]
	Color centers (F_2^- : LiF)	[96, 97]
CO_2 λ_L around 9.2 μm		
	Organic gases (CF_2Cl_2, HCOOH)	[99, 102]
λ_L around 9.6 μm		
	Organic gases (CH_3F, CH_3OH, HCOOH, C_3H_4, CH_3Cl, C_2F_3Cl)	[99–101] [103, 105]
λ_L around 10.6 μm		
	Organic gases (SF_6, PF_5, $CH_2{=}CHCl$, BCl_3, CF_2Cl_2, CO_2-propylene	[98, 99, 104, [106, 107]
	Color center (ReO_3^- : KCl)	[108]

For high-gain active media slow saturable absorbers are sufficient for short pulse generation, since the leading part is shortened by the absorber and the trailing part is shortened by the gain medium [18]. A detailed analysis indicates the following requirements for the passive mode-locking of high-gain lasers [18, 117]: i) the absorber has to saturate more easily than the gain medium in order to provide a net gain at the peak of the pulse and loss on either side. This condition requires $\sigma_A/A_A > \sigma_G/A_G$ where A_A and A_G are the laser beam cross-sections at the absorber and the gain medium, respectively. ii) The absorption recovery time of the saturable absorber τ_A has to be faster than the gain recovery time τ_G (equal to upper laser level lifetime) of the gain medium, i.e. $\tau_A < \tau_G$. This condition garanties the background suppression between the circulating pulse. iii) The absorption recovery time has to be less than the cavity round-trip time ($\tau_A < t_R$), otherwise a steady-state continuous emission would result after damped spiking.

The passive mode-locking may be combined with various methods of active mode-locking [118–123, 320]. Instead of absorption changes the intensity dependent refractive index may be applied to passive mode-locking [121, 124–130].

3.1. Passive Mode-Locking with Saturable Absorbers

The passive mode-locking in low-gain lasers and high-gain lasers is discussed separately.

a) Low-Gain Active Media. Passive mode-locking of lasers having low-gain active media (solid-state lasers [138–159], iodine lasers [166, 167], TEA-CO_2 lasers [43, 108, 162]) is illustrated in Fig. 4. In part (a) a linear oscillator is shown. The saturable absorber is located near a laser mirror. More often the absorber is contacted directly to a mirror (colliding pulse arrangement) [131] in order to increase the laser intensity in the absorber and to avoid the appearance of satelite pulses. Sometimes the colliding pulse arrangement is formed by placing the saturable absorber midway in the resonator [132] or in an antiresonant ring [133, 134].

The pictures (b) to (e) of Fig. 4 illustrate the mechanism of mode-locking (passive loss modulation). The left half characterizes an early stage of pulse development. The right half depicts the steady-state situation. Due to the low gain of the active medium the upper laser level population N_u remains practically constant within a round-trip period t_R in the case of

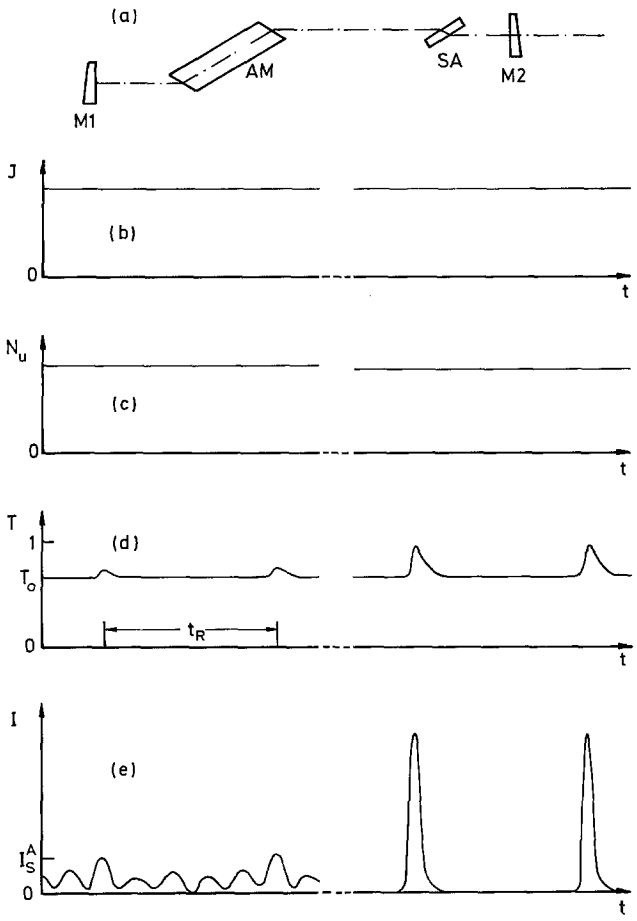

Fig. 4a–e. Passively mode-locked low-gain laser. (a) Schematic of a linear resonator setup. (M1, M2: laser mirrors, AM: active medium, SA: saturable absorber). (b) Pump rate J. (c) Upper laser level population. (d) Saturable absorber transmission. (e) Temporal pulse development. (b–e) Left half: early stage of pulse development. Right half: steady-state performance. t_R is the resonator round-trip time

constant pumping J. The transmission T of the saturable begins to increase as soon as a spike of the circulating radiation approaches the saturation intensity of the absorber. The small signal transmission is restored with the absorption recovery time τ_A. In the steady-state situation the amplification of the circulating radiation reduces the upper laser level population density (right side of Fig. 4c compared to left side). The population is below the threshold population for the small signal transmission T_0. Only the strongest spike survives. The radiation between the circulating pulse is suppressed.

In flashlamp-pumped passively mode-locked lasers, the pulse intensity often rises far above the saturation intensity ($I_L \gg I_S$) and the pulse shortening action is lost. In this case the nonlinear transmission period is too short to approach the steady-state situation, and the pulse duration remains longer than the steady-state limit. A linear loss feedback may keep the mode-locked pulse intensity in the nonlinear transmission region, prolong the pulse train length, and shorten the pulses down to the steady-state limit [112, 135–137].

The passive mode-locking is widely used for picosecond pulse generation with Nd:glass [15–17, 22, 29–32, 138–151, 186], Nd:YAG [133, 134, 149–152], and ruby lasers [22, 153–159]. It has also been successfully applied to mode-lock tunable solid-state lasers (alexandrite [132, 160]) and sensitized solid-state lasers (Nd:Cr:GSGG [161]). Atmospheric TEA-CO_2 lasers allow the generation of subnanosecond pulses by passive mode-locking with saturable semiconductors (p-type Ge [162]), color centers (ReO_4^-:KCl [108]) and molecular gases (SF_6 [162]) (for a review, see [43]). HeNe lasers have been mode-locked with Ne ($\Delta t_L \simeq 330$ ps) [164] and various saturable dyes ($\Delta t_L \simeq 220$ ps) [165] (for a review, see [43]). Iodine photodissociation lasers ($\lambda_L = 1.3152$ μm) have been mode-locked mainly with the saturable dye BDN II ($\Delta t_L \simeq 1.7$ ns) [166, 167]. Newly developed infrared dyes (S 301, S 401, S 501) [168] should be suitable to mode-lock iodine lasers.

It should be noted that the saturation intensity I_S^A is inversely proportional to the absorption recovery time τ_A. For very fast saturable absorbers the mode-locking threshold is difficult to approach since the peak spiking intensity of the laser remains below the saturation intensity [32] and special focusing geometries are necessary to achieve mode-locking [147, 170]. The use of two saturable absorbers of widely different saturation intensity (different τ_A) offers the possibility of low mode-locking threshold and short pulse generation [112, 171].

The high saturation intensity restricts generally the passive mode-locking to pulsed laser systems. Passive mode-locking of cw Nd:YAG lasers with an organic dye [172] and an F_2^+-center [173] has been reported.

The generation of intensive picosecond light pulses is often accompanied by self-phase modulation which causes broad-band chirped pulses [174]. The chirped pulses may be compressed by bandwidth-limiting filtering of the active medium [32, 121, 159, 175–178] inside the oscillator or by dispersive effects in grating pairs, prism pairs, or grating-prism combinations outisde the oscillator [179, 180].

In Table 2 some data of the most commonly used saturable absorbers for solid-state lasers are collected. Especially for Nd:lasers a considerable number of organic dyes [181–183] and color centers [173, 184, 185] have been investigated. For saturable absorbers with the absorption peak at the short-wavelength side of the laser wavelength only a fraction of molecules takes part in the absorption process. The absorption

Table 2. Saturable Absorbers for solid-state lasers

Absorber	Solvent	λ_A^{max} [nm]	τ_A [ps]	σ_A [cm^2]	I_S^A [W/cm^2]	Ref.
Ruby $\lambda_L = 694.3$ nm, $\Delta\tilde{\nu}_G = 11$ cm^{-1}, $\tau_G = 3$ ms						[187]
DDI	Methanol	704	17 ± 3	7.6×10^{-16}	2.2×10^7	[188, 189]
DCI	Ethanol	704	37	5.8×10^{-16}	1.3×10^7	[190]
DCI′	Ethanol	658	20			[191]
DTDCI	Ethanol	655	180			[191]
Alexandrite $\lambda_L = 701$–818 nm, $\tau_G = 262$ µs						[203]
DDI ($\lambda_L = 745$ nm)	Ethanol	709				[204]
DCI ($\lambda_L = 740$ nm)	Ethanol	709	37			[204]
3501*u* ($\lambda_L = 750$–780 nm)	Ethanol	732				[204]
4183*u* ($\lambda_L = 750$–780 nm)	Ethanol	722				[204]
Nd:glass: $\lambda_L \simeq 1.055$ µm, $\Delta\tilde{\nu}_G \simeq 200$ cm^{-1}, $\tau_G \simeq 350$ µs						[32]
Nd:YAG: $\lambda_L = 1.064$ µm, $\Delta\tilde{\nu}_G \simeq 4.5$ cm^{-1}, $\tau_G \simeq 250$ µs						[192]
Nd:Cr:GSGG: $\lambda_L = 1.0613$ µm, $\Delta\tilde{\nu}_G \simeq 12$ cm^{-1}, $\tau_G \simeq 250$ µs						[193]
A 9860	1,2-Dichloroethane	1066	7	3.7×10^{-16}	7.3×10^7	[194, 195, 196]
A 9740	1,2-Dichloroethane	1060	11	6.1×10^{-16}	2.8×10^7	[194, 196]
IR 5	1,2-Dichloroethane	1090	2.7	3×10^{-16}	2.3×10^8	[195, 196]
BDNI	Diethyl sulfide	1060	25	$\sim 1.1 \times 10^{-16}$	6.8×10^7	[92, 198]
3955	Nitrobenzene	1040	75	3.2×10^{-16}	7.9×10^6	[199, 200, 182]
3955	Methanol		35			[199]
3274-*u*	Nitrobenzene	1086	14	7.2×10^{-16}	1.9×10^7	[183, 182]
3274-*u*	Methanol		6			[183]
3321-*u*	Nitrobenzene	1134	0.35	2×10^{-16}	2.7×10^9	[147, 182]
4363	Polyurethane acrylate	1067	6			[152]
Z color center	Ba, Eu, Sr:RbBr		~ 50	10^{-18}–10^{-17}	3×10^8–3×10^9	[205]

DDI = 1,1′-diethyl-2,2′-dicarbocyanine iodide = DDCI
DCI = 1,1′-diethyl-4,4′-carbocyanine iodide-cryptocyanine
DCI′ = 1,1′-diethyl-2,4′-carbocyanine iodide = DCCI
DTDCI = 3,3′-diethyl-2,2′-thiadicarbocyanine iodide

cross-section of the interacting molecules is approximately equal to the stimulated emission cross-section at the laser frequency [201, 202].

b) High-Gain Active Media. The passive mode-locking of high-gain active media (dye lasers [22, 208, 211, 212], diode lasers [117, 270–272], excimer lasers [273–278], color-center lasers [207], HeNe lasers [43, 164, 165], Ar^+ lasers [169]) is illustrated in Fig. 5. Part (a) depicts a cw laser pumped colliding pulse mode-locked ring laser (CPM laser) [206]. This oscillator layout is used especially for femtosecond pulse generation in organic dyes [206] and color centers [207]. Linear resonators, like the arrangement of Fig. 4a, are in operation for pulsed and cw dye lasers, diode lasers, and excimer lasers. A comparison of Figs. 5c and 4c indicates the difference between high-gain and low-gain media. In the high-gain media the gain is saturated by the most intense fluctuation. The upper laser-level population falls below the threshold population in the trailing part of the circulating pulse. Slow saturable absorbers (Fig. 5d) are sufficient for mode-locking [18, 36, 37, 40, 41]. From the spontaneous emission (Fig. 5e, left half) the most intense fluctuation survives and circulates in the oscillator (right half).

Passively mode-locked dye lasers may be pumped by flashlamps, pulsed lasers, or cw lasers (argon-ion lasers, krypton-ion lasers) [22, 43, 208].

The passive mode-locking was first achieved in a flashlamp-pumped rhodamine 6G laser with the saturable absorber DODCI [209]. The flashlamp-pumped organic dye laser oscillators generate intense, frequency tunable, light pulses of several picoseconds duration and several tens of megawatt power [22, 208, 210, 211]. Using different lasing dyes and saturable absorbers passive mode-locking has been achieved in the wavelength region between 450 and 840 nm. [Ref. 212, Table 2.1] gives an overview of the covered spectral region (references are cited there). The passive mode locking of flashlamp-pumped dye lasers has been reviewed in [22, 208, 211, 212]. Data on lasing dyes and saturable absorbers have been collected in [213, 214].

Passive mode-locking with pulsed pump lasers has been discussed in [215, 216]. In a colliding pulse ring arrangement pulses of 340 fs duration were generated using 100 µs long pulses of a xenon ion pump laser (lasing dye rhodamine 6G, absorber DODCI) [216].

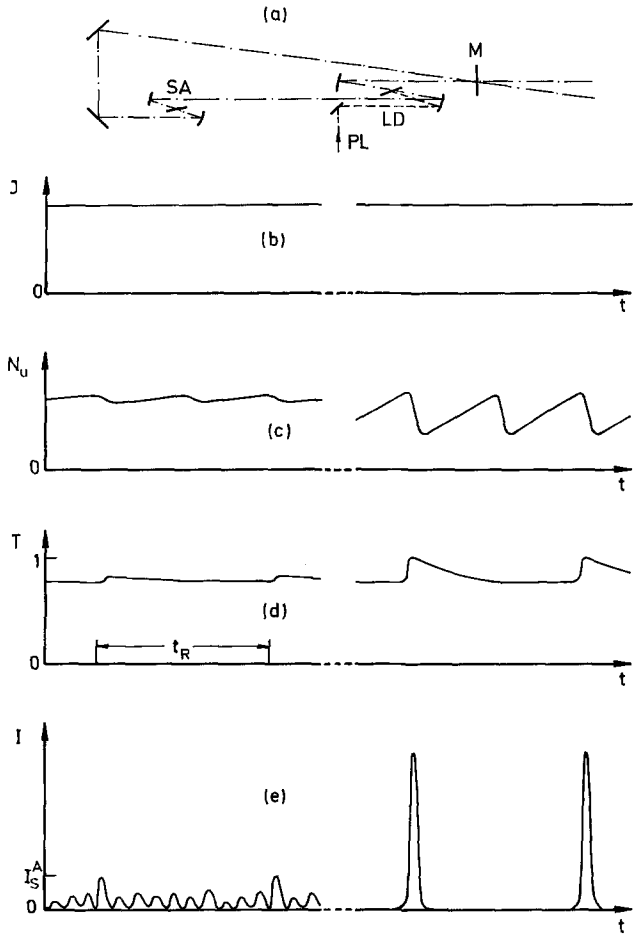

Fig. 5a–e. Passively mode-locked high-gain laser. (a) Schematic setup of a CPM ring laser. (PL: pump laser, LD: lasing dye jet, SA: saturable absorber jet, M: output coupler). (b) Pump rate J. (c) Population of upper laser level. The two counter-propagating pulses pass through the active medium at time intervals of $t_R/2$. (d) Saturable absorber transmission. (e) Temporal pulse development. (b–e) Left half: early stage of pulse development. (Right half: steady-state situation)

The high gain of organic dyes allows the passive mode-locking with cw argon-ion and krypton-ion lasers [347, 348, 22, 208, 212]. Generally double Z-folded cavities with separate gain and absorber jets are used in linear (standing wave) [217–218] or ring resonators [206]. In early experiments dye cells were used instead of jets [219, 347, 348]. Sometimes the lasing dye and the saturable absorber are mixed and only a single jet is used [218]. Frequency tuning is achieved with wedges, prisms, etalons, or birefringent filters. The pulse repetition rate is of the order of 100 MHz and the average output power is several tens of milliwatt (single pulse energy ~ 100 pJ).

Using various lasing dyes and saturable absorbers the wavelength region between 460 and 974 nm (with gaps) has been covered by cw passive mode-locking. The performance data are collected in Table 3. In simple linear resonators pulse durations down to 150 fs have been achieved [220]. The femtosecond pulse generation could be stabilized by mixing a slow and fast saturable absorber [221, 253]. Pulse durations down to 340 fs were reported [253]. In a linear antiresonant ring-cavity pulses with durations down to 130 fs were generated [233]. In a linear colliding pulse mode-locked (linear CPM) laser-pulse duration down to 50 fs were obtained (absorber jet thickness $d_{jet} = 50$ μm, gain jet thickness 100 μm) [223]. In CPM ring lasers the shortest pulse duration achieved was 47 fs [225]. Transient grating effects in thin saturable absorber jets ($d_{jet} \lesssim c_0 \Delta t_L / n_A$, n_A refractive index of absorber, $d_{jet} \lesssim 10$ μm for $\Delta t_L = 50$ fs) of CPM lasers stabilize the mode-locking [206, 225–228] and facilitate the extremely short pulse generation.

The short pulses in the resonator are chirped by phase changes in the dielectric mirrors [299–231], self-phase modulation [232–235] and group-velocity dispersion [235] in the optical components. Chirp compensation in the resonator has been achieved by insertion of glass plates [236, 237], prism pairs [222, 224, 238, 239], and Gires-Tournois interferometers [197, 240]. For a prism-pair compensated linear resonator pulse durations down to 120 fs were reported [249]. In a linear antiresonant ring cavity with intracavity prisms pulses with duration down to 50 fs were generated [224]. Intracavity balancing of self-phase modulation, group-velocity dispersion, saturable absorption, and saturable gain allowed the generation of pulses as short as 27 fs [241, 242]. The external combination of optical fibers (spectral broadening, chirp formation) and diffraction gratings (compression) offers the possibility to shorten the generated pulses [243–245]. Using an optical fiber and a combination of two prism pairs and a grating pair, pulse durations of 6 fs – so far the shortest pulses – have been achieved [246].

The passive mode-locking of a color-center laser has been demonstrated recently [207]. A F_2^+:LiF crystal was pumped with a cw chopped krypton-ion laser. An IR 140 dye solution was used as saturable absorber. In a colliding-pulse mode-locking arrangement pulses were generated at wavelengths around 870 nm with durations down to 390 fs. Suggestions are made to extend the technique to F_2^+:NaF and F_2^+:NaCl crystals and other saturable absorbers. A tuning range between 1.0 and 1.7 μm is expected.

Passive mode-locking of cw semiconductor diode lasers was achieved by putting the diode in an external resonator. An unpumped pn region is used as saturable absorber [270, 271]. Recently a radiation-damaged multiple quantum well structure (AlGaAs/GaAs) has been successfully applied for passive mode-locking ($\tau_A \simeq 150$ ps, $\tau_G \simeq 400$ ps) [117]. Pulse durations down

Table 3. Cw passively and hybridly mode-locked dye lasers

Dye[a]	Absorber[a]	Tuning range [nm]	Shortest duration [fs]	Pump source	Resonator	Ref.
Passively mode-locked						
Coumarin 102	DOCI	~460	580	UV Ar^+	lin, 2 jets	[249]
Rhodamine 110	HICI	553–570	152	Ar^+	lin, 2 jets	[220]
	DASBTI	553–570	210	Ar^+	lin, 2 jets	[220]
	DASBTI	583	120	Ar^+	bal, lin, 2 jets	[249]
	DASBTI	583	70	Ar^+	bal, ring CPM	[249]
	HICI	585	< 100	Ar^+	bal, ring CPM	[249]
Rhodamine 6G	DASBTI	570–600	520	Ar^+	lin, 2 jets	[250]
	DQOCI	583–584	100	Ar^+	lin CPM	[223]
	DODCI + DQOCI	586–592, 619–621	100	Ar^+	lin CPM	[223]
	DODCI	590–610	400	Ar^+	lin, 1 jet	[251]
	DODCI	598–615	300	Ar^+	lin, 1 jet + 1c.cell	[219]
	cresyl violet	610–620	900	Ar^+	lin, 1 jet + 1c.cell	[252]
	DODCI + malachite green	608–614	340	Ar^+	lin, 2 jets	[253]
	DODCI	618	47	Ar^+	ring CPM	[225–227]
	DODCI	615	27	Ar^+	bal, ring CPM	[241, 242]
	DODCI	615	6	Ar^+	ring CPM, ext.comp.	[246]
	DODCI	612–630	130	Ar^+	lin A.R.	[233]
	DODCI		50	Ar^+	bal, lin A.R.	[224]
	DODCI	612–622	50	Ar^+	lin CPM	[223]
Rhodamine B	DQTCI	616–658	220	Ar^+	lin, 2 jets	[254]
	cresyl violet	610–620	3000	Ar^+	lin, 1 jet + 1c.cell	[252]
Rhodamine 6G + Sulforhodamine 101	DQTCI	652–681	120	Ar^+	lin, 2 jets	[255]
	DCI′	652–694	240	Ar^+	lin, 2 jets	[255]
DCM	DQTCI	655–673	680	Ar^+	lin, 2 jets	[256]
Rhodamine 700	DOTCI	727–740	1000	Kr^+	lin, 2 jets	[257]
	DOTCI + DCI	740	350	Kr^+	lin, 2 jets	[257]
	HITCI	762–778	850	Kr^+	lin, 2 jets	[256]
Hybridly mode-locked						
Disodium fluorescein	Rhodamine B	535–575	450	m.l.Ar^+	1 jet, lin	[258]
Rhodamine 110	Rhodamine B	545–585	250	m.l.Ar^+	1 jet, lin	[258]
	DODCI	561	580	m.l.Ar^+	1 jet, lin	[258]
	DASBTI	560	283	Nd:YAG	2 jets, bal, lin	[259]
Rhodamine 6G	DODCI + DQOCI	583	69	Nd:YAG	2 jets, bal, lin	[222]
	DODCI	622	< 150	Nd:YAG	2 jets, bal, lin	[222]
	DODCI	574–611	300	m.l.Ar^+	1 jet, lin	[299]
	DODCI	595–620	85	Nd:YAG	2 jets, lin A.R.	[260]
	DODCI	615–625	130	m.l.Ar^+	2 jets, lin A.R.	[261]
	Pinacyanol	590–625	160	m.l.Ar^+	2 jets, lin A.R.	[261]
	DODCI	620	100, 60	m.l.Ar^+	2 jets, ring CPM	[262, 268]
	DQOCI	615	70	Nd:YAG	1 jet, lin	[263]
Rhodamine B	DTDCI	628	320	Nd:YAG	2 jets, bal, lin	[264]
	Oxazine 720	649	187	Nd:YAG	2 jets, bal, lin	[264]
Rhodamine 101	DQTCI	675	59	Nd:YAG	2 jets, bal, lin	[264]
Sulforhodamine 101	DQTCI	675	55	Nd:YAG	2 jets, bal, lin	[264]
Pyridine 1	DDI	695	103	Nd:YAG	2 jets, bal, lin	[265]
Pyridine 2	DDI	733	263	Nd:YAG	2 jets, bal, lin	[265]
	DOTCI	733	263	Nd:YAG	2 jets, bal, lin	[265]

Table 3 (continued)

Dye[a]	Absorber[a]	Tuning range [nm]	Shortest duration [fs]	Pump source	Resonator	Ref.
Oxazine 725	HITCI	750–780	800	m.L.Kr^+	1 jet, lin, cavity-dumped	[266]
Oxazine 750	HDITC-perchlorate	750–835	800	m.L.Kr^+	1 jet, lin	[267]
Styril 8	HITCI	800	70	Nd:YAG	2 jets, bal, lin	[265]
Styril 9	IR 140	840–880	65	m.L.Ar^+	2 jets, ring CPM	[268]
	IR 140	800–840	137	Nd:YAG	2 jets, bal, lin	[265]
Styril 14	DaQTeC	974	228	Nd:YAG	2 jets, bal, lin	[269]
	DQTrCI	897–905	265	Nd:YAG	2 jets, bal, lin	[269]

Ar^+: cw argon ion laser. Kr^+: cw krypton ion laser. Nd:YAG: frequency doubled cw mode-locked Nd:YAG laser. m.L.Ar^+: mode-locked cw argon ion laser. m.L.Kr^+: mode-locked cw krypton ion laser. lin: linear resonator. bal: prism balanced resonator. CPM: colliding pulse mode-locked laser. ext.comp.: externally compressed. A.R.: anti-resonator ring colliding pulse arrangement

[a] Dye and absorber data are found in [213, 214]

to 1.6 ps have been obtained. The pulses had a positive group velocity dispersion and could be compressed externally with a grating-prism pair down to 0.8 ps [272].

Rare-gas halide excimer lasers are powerful light sources in the UV spectral region [273]. Passive mode-locking of discharge-pumped excimer lasers has been achieved for XeCl ($\lambda_L = 308$ nm, absorber BBQ, duration $\Delta t_L = 2$ ns) [274] and KrF ($\lambda_L = 248.5$ nm, absorbers: 7-diethylamino-4-methylcoumarin, *p*-terphenyl, and aurimine *D*, $\Delta t_L \leqq 2$ ns) [275]. A series of saturable absorbers have been investigated [50, 277, 278]. The excited-state absorption and the dye dissociation and fragmentation are problems for UV saturable absorbers. In high-power excimer lasers the nonlinear absorption of the solvent (mainly two-photon absorption) may act against dye bleaching.

HeNe lasers have been cw mode-locked at $\lambda_L = 632.8$ nm with Ne ($\Delta t_L \simeq 330$ ps) [164] and various saturable dyes (cresyl voilet, Nile blue, Nile blue A, Resazurin, DODCI, and DTDCI, $\Delta t_L \simeq 220$ ps) [165]. Passive mode-locking of an argon ion laser was carried out with rhodamine 6G [169].

The saturable absorbers themselves may act as active media. Using proper mirror reflectivities the simultaneous ultrashort pulse formation of the emissions of the gain medium and of the absorber medium occurs [248, 344]. The cw passive double mode-locking has been achieved with rhodamine 6G ($\lambda_{L,1}$ around 580 nm) and cresyl violet ($\lambda_{L,2}$ around 640 nm) [247, 345, 346]. Passive double mode-locking is also reported for a HeNe laser with several saturable dyes [165] and an argon ion laser with rhodamine 6G [169].

3.2. *Hybrid Mode-Locking*

For low-gain lasers the passive mode-locking is often combined with active loss modulation. For high-gain lasers the passive mode-locking and the synchronous pumping are combined.

a) Low-Gain Active Media. The simultaneous active and passive mode-locking of low-gain lasers is illustrated in Fig. 6. The laser oscillator (Fig. 6a) consists of the active medium, the saturable absorber cell, and the active loss modulator (generally an acousto-optic modulator [279–281]). For constant pumping (Fig. 6b) the upper-laser-level population (Fig. 6c) remains practically unchanged within a round-trip time t_R. As long as the circulating radiation intensity in the oscillator is well below the saturation intensity I_S^A of the saturable absorber, the transmission of the saturable absorber is equal to the small-signal transmission T_0, and the mode-locking is performed by the active loss modulator (left half of Fig. 6). In the steady-state region (right half of Fig. 6) an intense pulse has been built up. It bleaches the saturable absorber. The active loss modulation causes mode-locking even at low intensities ($I_L < I_S^A$). The passive mode-locking shortens the generated circulating pulse. The combined active-passive mode-locking stabilizes the mode-locking dynamics. It allows the synchronization of lasers.

The active-passive mode-locking is widely applied for solid-state lasers (Nd:YAG [282–285], Nd:glass [136, 286–290, 328, 332], ruby [291]). The active and passive mode-locking may be combined with cavity-dumping [285]. A theoretical investigation of the active-passive mode-locking is presented in [283, 292].

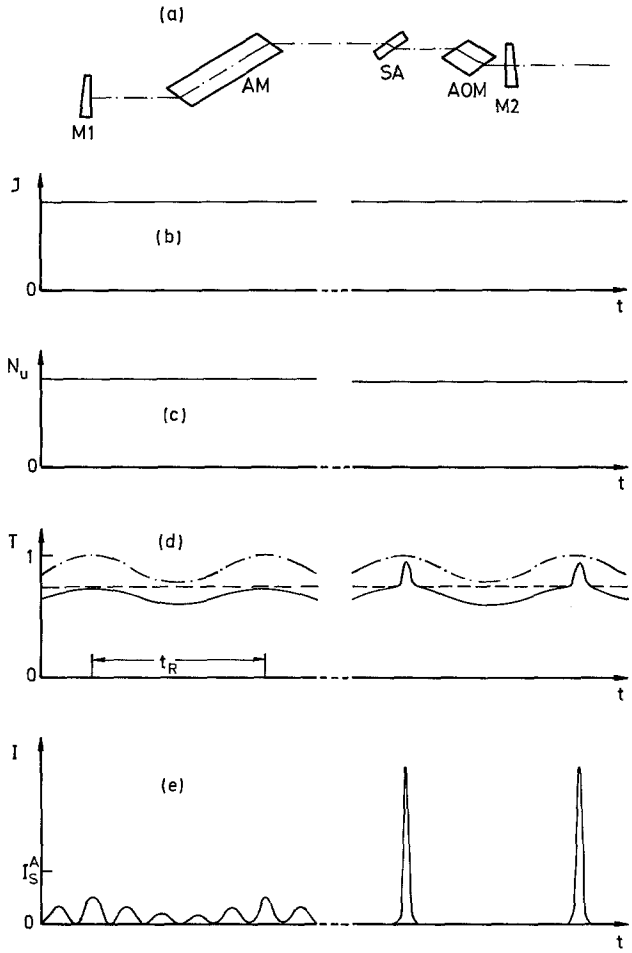

Fig. 6a–e. Hybridly mode-locked low-gain laser. (a) Linear resonator arrangement of an active-passive mode-locked laser. (M1, M2: laser mirrors, AM: active medium, SA: saturable absorber. AOM: acousto-optical modulator). (b) Pump rate J. (c) Upper laser level population N_u. (d) Temporal light transmission. Dashed curve, saturable absorber. (Dash-dotted curve: acousto-optical modulator, solid curve: total transmission through absorber and acousto-optical modulator). (e) Temporal pulse development. (b–e) Left half: early stage of pulse development. Right half: steady state situation

Besides the active-passive mode-locking with acousto-optic modulators other hybrid mode-locking techniques have been developed. Self-injected (cavity-flipped) passively mode-locked lasers have a Pockels-cell shutter and an absorber cell inside the resonator [293, 294]. The voltage across the Pockels cell is varied step-wise in a well defined sequence. First inversion is accumulated (low Q-value), then the resonator Q-factor is switched to a high value and an intense laser radiation is built up. Before inversion depletion the radiation in the cavity is dumped for a period less than the round-trip time. The remaining pulse in the cavity (seeding pulse) is amplified by the gain medium and shortened by the nonlinear transmission through the saturable absorber. Towards the end of the pulse development the generated pulse is cavity-dumped. The self-injection and passive mode-locking has been applied to Nd:lasers [293, 294].

The simultaneous passive and kinematic mode-locking (one laser mirror is vibrated) of cw Nd:YAG lasers is analyzed in [295, 296].

The synchroneous pumping of a germanium-switch with a mode-locked Nd:glass laser allowed the extraction of picosecond light pulses from a TEA-CO_2 laser [297, 298]. The transparent Ge at 10.6 μm is made highly reflective by the large free-carrier generation with 1.06 μm pulses.

b) High-Gain Active Media. The most common technique of hybrid mode-locking of dye lasers is the simultaneous synchronous pumping and passive mode-locking. The lasing dye and the saturable dye may be circulated through two separate jets (Fig. 7a) [222, 259–262, 264, 265, 268, 269] or may be mixed and pumped through one jet [258, 263, 266, 267, 299]. A contacted dye cell for the saturable absorber is used in [300].

The synchronous pumping and passive mode-locking is illustrated in Fig. 7. A mode-locked pump laser inverts the dye molecules in the lasing dye jet. The round-trip time of the synchronously pumped laser cavity has to be adjusted accurately to the pulse separation of the pump laser train [123, 301, 302]. The pulsed excitation of Fig. 7b populates the upper laser level according to Fig. 7c. At an early stage of mode-locking (left half) the upper laser level population decays with the fluorescence lifetime τ_G. This lifetime has to be less than the cavity round-trip time ($\tau_G < t_R$) in order to achieve mode-locking by synchronous pumping (otherwise only passive mode-locking occurs). As soon as the peak intensity of the circulating radiation at the saturable absorber jet approaches the saturation intensity I_S^A, the transmission through the absorber increases and the passive mode-locking shortens the pulses generated already by the synchronous pumping.

The performance data of synchronously pumped and passively mode-locking cw dye lasers are collected in Table 3. A wavelength region between 535 and 974 nm is covered (with gaps).

The synchronous pumping of colliding pulse mode-locked ring dye lasers was studied in [262, 268, 303]. In [303] the distance between the gain jet and the absorber jet is exactly a quarter of the ring perimeter. The pump pulse separation is half the dye laser round-trip time t_R. The dye-laser pulses generated by subsequent pulses collide in the absorber jet. In [262, 268] the distance between the gain jet and the absorber jet is set to one fifth of the perimeter. The gain jet is pumped by an asymmetric sequence of pump pulses at times $t = 0$, $3/5t_R, t_R, 8/5t_R, 2t_R, \ldots$. This sequence is obtained with a

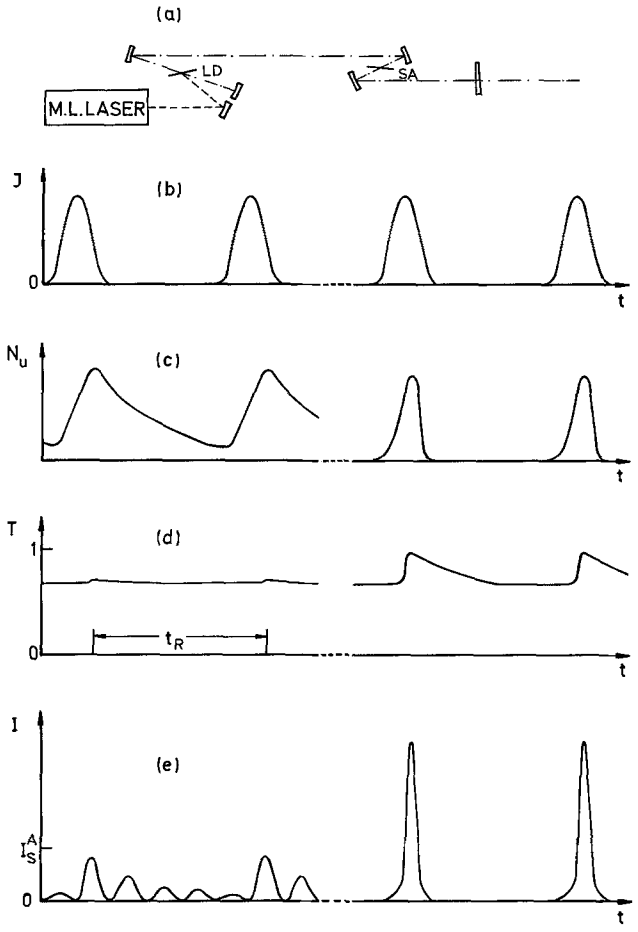

Fig. 7a–e. Hybridly mode-locked high-gain laser. (a) Experimental setup of a synchronously pumped and passively mode-locked laser with two jets in the resonator. LD: amplifying dye jet, SA: saturable absorber jet. (b) Pump rate J. (c) Upper laser level population N_u. (d) Transmission through saturable absorber. (e) Temporal pulse development. (b–e) Left half: early stage of pulse development. Right half: steady-state situation

beam splitter and an optical delay line. Dye laser pulses generated by subsequent pump pulses collide in the absorber jet.

The synchronous pumping in linear cavities with colliding pulse mode-locking in an anti-resonant ring is described in [261]. Cavity-dumping of hybridly mode-locked lasers is used in [266, 304] to increase the output-pulse energy (for cavity dumping of cw passively mode-locked lasers, see [218]). Hybridly mode-locked lasers are synchronized easily to other lasers.

The intracavity [222, 259, 264, 265, 268, 269] and extracavity [317] pulse compression methods, mentioned in Sect. 3.1b for passively mode-locked lasers, are also applied to hybrid mode-locked lasers.

In the laser systems mentioned above, cw mode-locked lasers were used for synchronous pumping. Recently femtosecond dye laser pulses were generated by passive mode-locking and synchronous pumping with prolonged second harmonic pulse trains of a passively mode-locked Nd:glass laser [318]. 90 fs pulses of 100 nJ energy could be generated. A single-stage amplifier produced single pulses of 150 fs duration and 10 μJ energy. The amplified pulses were compressed to 68 fs with a grating pair. In [319] 0.8 ps pulses of 1.6 μJ energy have been generated in a synchronously pumped dye laser combined with an external saturable absorber-amplifier compressor (Sect. 5.2). The synchronous pumping was achieved with a pulsed frequency-doubled passively mode-locked Nd:YAG laser.

The cw passively and hybridly mode-locked dye lasers generate single pulse energies in the region of 0.1 nJ. Various amplification schemes have been developed to amplify – at a reduced repetition rate – the pulses to the μJ and mJ region [212]. N_2 lasers [251], Nd:YAG lasers [167, 305–310], copper-vapor lasers [276, 311, 312], and excimer lasers [313–315] are used for pumping the amplifier dye cells. 12 nJ pulses of 100 fs duration could be generated at a repetition rate of 3 MHz with a cavity dumped argon ion laser as a pump source for the amplifier [316].

Besides the synchronous pumping of the active medium, the synchronous pumping of the saturable absorber was applied to mode-lock and synchronize a slave oscillator to a master oscillator [320, 321]. A similar technique uses picosecond pulse trains to open ultrahigh-speed semiconductor switches [322] which transmit high-voltage pulse trains to Pockels-cell modulators of lasers that should be mode-locked. This technique was applied to mode-lock a XeCl excimer laser [323] and a GaAs/GaAlAs semiconductor laser [324].

The active loss modulation with an acousto-optic modulator may also be combined with the passive mode-locking for the ultrashort-pulse generation in cw dye lasers [325] and flashlamp-pumped dye lasers [326]. The active loss modulation and passive mode-locking of a XeCl-excimer laser allowed the generation of 300 ps pulses [327]. RF pump pulse modulation and passive mode-locking was combined for subpicosecond pulse generation in a semiconductor laser [271].

3.3. Passive Mode-Locking by Refractive-Index Changes

A medium with intensity-dependent refractive index placed inside the laser oscillator couples the cavity modes by phase modulation. A theoretical analysis of this mode coupling has been given in [124–126]. Mode-locking experiments were carried out with different optical Kerr media in ruby lasers [128] and Nd:glass lasers [127, 129, 130].

The pulse compression inside an actively mode-locked Nd:YAG laser by pulse chirping in a liquid Kerr cell (self-phase modulation) has been reported in [121]. The intracavity pulse compression of chirped pulses in a passively mode-locked laser by the finite spectral gain width of the active medium has been discussed in Sect. 3a [32, 121, 159, 175–178].

The simultaneous action of self-phase modulation and negative group velocity dispersion in synchronously pumped color-center lasers incorporating a glass fiber feedback path led to soliton-pulse formation of adjustable femtosecond duration (soliton laser) [329, 330].

4. Simultaneous Q-Switching and Mode-Locking

The pulsed passive mode-locking of flashlamp-pumped solid-state lasers is often called mode-locking of a Q-switched laser [24, 331] due to the similarity to Q-switched laser operation. To achieve mode-locking, the spectral gain narrowing elements of Q-switched lasers are removed.

The simultaneous Q-switching and passive mode-locking is applied in the mode-locked self-injection lasers described in Sect. 3a [293, 294]. The time jitter in a hybridly mode-locked Nd:glass laser was considerably reduced by simultaneously Q-switching the laser with a mechanical chopper (jitter without chopper ± 15 µs, jitter with chopper $\leqq \pm 300$ ns) [332].

5. Pulse Shortening with Saturable Absorbers

Besides passive mode-locking, the saturable absorbers are employed to suppress background radiation [333], to decouple amplifiers (suppression of amplified spontaneous emission signals) [276, 278, 306–311, 315, 334] and to shorten light pulses [46, 48, 276, 335–341]. It should be noted that the self-induced ellipse rotation of Kerr liquids between polarizers and retardation plates may be used as well for passive background suppression and gain isolation [328].

5.1. Pulse Shortening in Master-Slave Oscillator Systems

A master-slave oscillator arrangement for short-pulse generation is illustrated in Fig. 8a [336]. The pulse generation starts in a passively mode-locked laser oscillator (active medium AM 1). After an intense pulse has been built up, the pulse polarization is rotated 90° with Pockels cell PC 1 and the pulse continues to circulate in the slave oscillator (active medium AM 2). The low saturable-absorber transmission of the slave

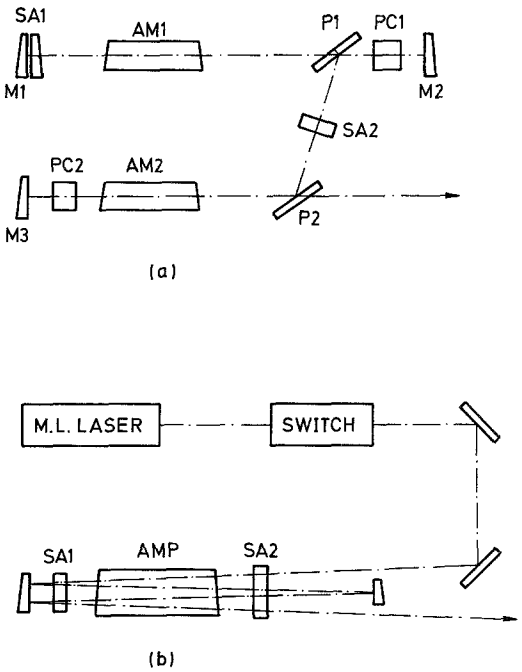

Fig. 8. (a) Pulse shortening in master-slave oscillator. (AM1: active medium of master oscillator. AM2: active medium of slave oscillator. P1, P2: polarizers. PC1, PC2: Pockels cells, SA1, SA2: saturable absorber cells, M1–M3: laser mirrors). (b) Pulse shortening in multi-pass absorber-amplifier system. (SA1, SA2: saturable absorber, AMP: amplifier medium)

oscillator (regenerative amplifier, absorber cell SA 2) shortens considerably the pulse duration. After several round trips the shortened pulse is switched out by voltage application to the Pockels cell PC 2.

With the described system Nd:glass laser pulses were shortened to 0.9 ps. In a similar branched-oscillator setup the Nd:glass laser pulses were shortened to 0.4 ps [337]. A ring regenerative amplifier was used in [338] for pulse shortening with saturable absorbers. In [339] a CS_2 cell was applied for self-switching from the master to the slave oscillator.

5.2. Extra-Cavity Pulse Shortening

The passing of light pulses outside the oscillator through an absorber cell shortens the pulse duration and reduces the background noise [48, 335, 340]. This pulse shortening technique was applied to Nd:glass lasers [48, 335] ruby lasers [159], excimer lasers [50, 341–343] and dye lasers [319].

A multi-pass absorber-amplifier arrangement is shown in Fig. 8b. Using a similar arrangement passively mode-locked Nd:glass laser pulses were shortened to 0.5 ps [48, 335].

The onset of laser action in excited saturable absorbers shortens the absorption recovery time and

leads to enhanced pulse shortening [50]. Putting a saturable absorber cell perpendicular into the light path may lead to sufficient feedback for laser action (enhanced amplified spontaneous emission). The combined saturable absorption and enhanced amplified spontaneous emission was applied to shorten excimer laser pulses [50].

6. Conclusions

The passive Q-switching and mode-locking as well as the hybrid Q-switching and mode-locking of solid-state lasers, dye lasers, semiconductor lasers, color-center lasers, and gas lasers (HeNe, Ar^+, iodine, CO_2, excimer) has been reviewed. The passive Q-switching and mode-locking techniques are competitive to the active Q-switching and mode-locking techniques. They have the advantage of greater simplicity and they allow the generation of shorter pulse durations.

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