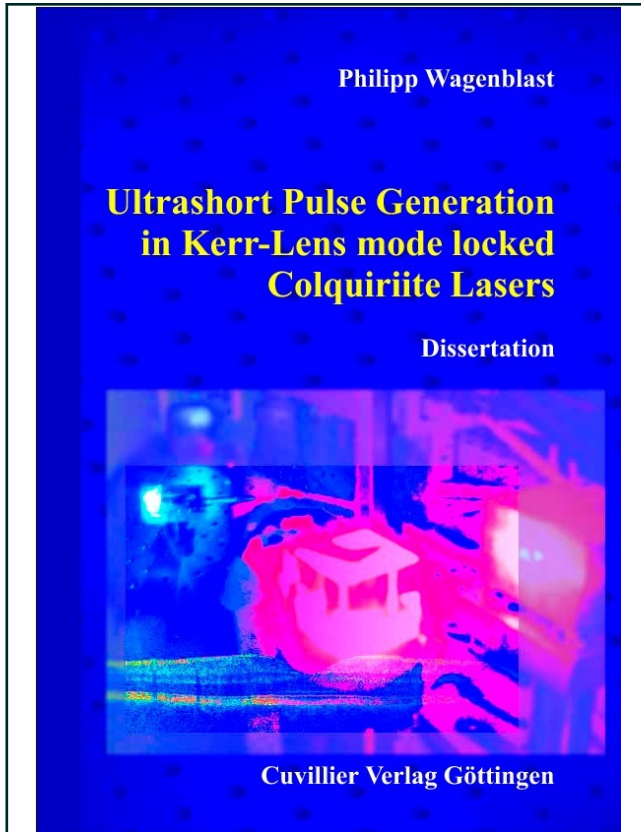




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**Ultrashort Pulse Generation in Kerr-Lens Mode  
Locked Colquiriite Lasers**



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# Chapter 1

## Motivation

One of the most fascinating achievements of modern Physics are the ultrashort light pulses emitted from mode locked lasers. Scientists are able to control the properties of light extensively down to the femtosecond regime, which corresponds to few cycles of the harmonic oscillation of the electric field. Besides an unprecedented temporal precision for the study and control of ultrafast phenomena, the concentration of electromagnetic energy to such short time intervals yields immense peak powers. Over the last years, the technique of Kerr-lens mode locking (KLM) steadily gained importance in the field of ultrashort pulse generation, and today it is the most influential one. The spatial focussing effect of the nonlinear Kerr lens favors pulsed operation over continuous operation and locks a large number of longitudinal laser modes in phase. Mode locked lasers therefore do not only emit short pulses, but also deliver broad, highly accurate frequency combs for metrology. For the generation of pulses shorter than 10 fs, Titanium doped sapphire is the dominantly used laser material. While Ti:sapphire exhibits attractive optical properties, such as a broad amplification bandwidth and high laser amplification, it does have one major drawback, namely a requirement for pumping with a green source. It requires either a costly argon ion laser or a frequency doubled solid-state pump source. For this reason, alternative materials to Ti:sapphire for direct diode pumping have experienced great attraction in KLM lasers. In 1980, novel alkali fluoride host crystals were discovered in the tin mines of Colquiri, Bolivia, and were named Colquiriites after this place. Doped with Cr, these crystals are suitable as laser crystals which can be pumped directly by red laser diodes, and moreover exhibit a gain bandwidth which is close to that of Ti:sapphire. The exploitation of KLM in diode-pumped Colquiriite lasers became a main motivation for the investigation of the underlying physical processes to this technique in recent years. The properties of nonlinear resonators and their implications for KLM still are not fully understood.

This thesis represents an important contribution to the understanding of Kerr-lens mode locking in diode-pumped lasers. An extensive treatment of gain guiding mechanisms and of the resonator stability properties is presented, and the implications of these effects for the mode locking mechanism and for laser efficiency are investigated. The extension of the standard model of resonators for KLM opens a way to the exploitation of gain

guiding for an efficient generation of ultrashort laser pulses. By the theoretical analysis of nonlinear resonators, a novel regime of KLM is found, and is applied to the mode locking of diode-pumped lasers for the first time. A heavy doping of the laser crystal enhances the influence of gain guiding on the resonator stability condition in a way that the nonlinear effect of the Kerr lens fundamentally changes the kind of the resonant mode. The strength of the mode locking mechanism is increased significantly, that apertures in the resonator become obsolete. Transferring these new insights in an experimental diode-pumped laser results in the generation of pulses with a duration of only 9.3 fs, which are the shortest by this kind of laser. Furthermore, the efficiency of diode-pumped ultrashort pulse lasers is increased by one order of magnitude. Experimental investigations conducted with this laser confirm the predictions of the model of nonlinear resonators to a large extent.

As an application of the novel femtosecond laser, it is implemented as a light source for Optical Coherence Tomography. This widespread used biomedical imaging technique is mainly applied for ophtalmic diagnosis of ocular diseases by imaging of the human retinal tissue. Mode locked lasers offer highest spatial resolution as light sources for this technique. Using the novel diode-pumped light source, images with equally matched quality are obtained as compared to more costly Ti:sapphire lasers, both with respect to image resolution and contrast. This application demonstrates the potential use of broadband, diode pumped Colquiriite lasers in the technical field, and opens a route to an economic use of femtosecond technology in medicine.

In conclusion, the present work is a significant contribution to the understanding of nonlinear resonators and the mechanism of Kerr-lens mode locking in diode-pumped lasers. The transfer of these insights to experimental lasers results in shorter pulse durations and in a more efficient use of pump power, and will enable further progress in the development of diode-pumped femtosecond light sources. Pulsed lasers are one of the key technologies of the early 21st century, and cost reduction will open new areas of application. The importance of diode-pumped femtosecond lasers will even grow in the future.

The thesis is organized in the following way: Fundamental physics relevant to ultrashort pulse generation is presented in Chapter 2. The basics of laser physics are recapitulated with emphasis placed on a linearized model of saturated laser amplification. Linear and nonlinear pulse propagation, and concepts of mode locking are presented in some detail. The chapter gives a brief introduction to Kerr-lens mode locking and dispersion compensation techniques.

Chapter 3 describes the model of nonlinear optical resonators which is utilized to determine the resonant laser mode by a matrix formalism in paraxial approximation. An extension to previous treatments of gain guiding incorporates gain saturation into the matrix formalism separately from laser power calculations. This chapter introduces the basic tool for the resonator design.

In Chapter 4, many aspects of novel experimental Colquiriite lasers are presented. Starting from the properties of Colquiriites, and the implications of diode pumping, the experimental implementation of mode locked Colquiriite lasers is presented in great de-

tail. The setups of a Cr:LiCAF laser, pumped by a tunable Ti:sapphire laser, and a diode-pumped Cr:LiCAF laser are described, and experimental results are presented and compared with the predictions of the resonator model of Chapter 3.

In Chapter 5, Optical Coherence Tomography is demonstrated as a biomedical application of the novel diode-pumped source. The diode-pumped LiCAF laser is used for the imaging of human retinal tissue with this technique. The experimental arrangement and results are presented.

Finally, the thesis concludes with a brief summary.



# Chapter 2

## Dynamics of ultrashort pulse lasers

The generation of ultrashort laser pulses requires control of dynamics on time scales ranging from the radiative lifetime of the inverted laser material  $\tau_L$  which is in the order of microseconds, to the radio frequency scales  $1/T_R$  of the repetition rate of the laser resonator which are typically nanoseconds, down to the actual duration  $\tau_p$  of the pulses of a few femtoseconds. Processes like gain buildup, gain saturation and photon decay take place on the longest timescale  $\tau_L$ . The actual laser power is determined by the dynamics on this timescale. By the choice of the laser material, the pumping process and by loss control, the laser efficiency and output power are determined. In the intermediate range from microseconds to nanoseconds, we meet with processes like relaxation oscillations, Q-switching instabilities and the build-up of mode locked pulses. The interaction between the inversion and the optical field is governing this regime. Instabilities on this timescale can be avoided by tailoring the saturable loss and gain dynamics, and by the choice of the laser material. Finally, on the shortest timescale, the dynamics of pulse formation by the interplay of nonlinear loss or gain, and pulse broadening or compression by dispersion takes place.

This chapter is organized as follows: First, the dynamics of photon density and inversion will be presented starting from basic rate equations. This leads to steady-state expressions for the laser power. The calculation of saturated laser amplification involving the spatial distribution of inversion and laser intensity will be presented, leading to a linearized expression for gain saturation. Then, dynamics of pulse propagation in linear and nonlinear dispersive media will be treated. The next section gives an illustrative description of common mode locking techniques by saturable absorber action. The mathematical description by the master equation of mode locking follows. The chapter is concluded by the discussion of Kerr-lens mode locking and general dispersion compensation schemes.

### 2.1 Rate equations

A pair of coupled differential equations describes the dynamical interplay of the population inversion and the photon density. An extensive treatment of these rate equations

can be found in most textbooks on lasers, particularly in [Sie86, Koe99]. This pair of equations governs laser buildup, laser amplification and saturation, and the dynamics of continuously and quasi-continuously operating (cw-continuous wave) lasers. We assume

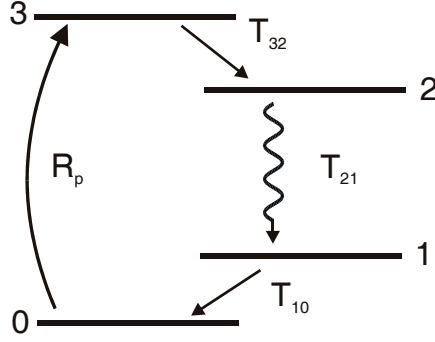


Figure 2.1: Schematic of a four-level system. The radiative laser transition is from level  $2 \rightarrow 1$ . The system is inverted by the pump process with a pump rate  $R_p$ .

four-level systems with an electronic level scheme as depicted in Fig. 2.1. The pump process lifts the system from ground state level 0 to an upper state level 3 with the pump rate  $R_p$ . With the relaxation from the upper-state level 3 to the upper level of the laser transition 2,  $T_{32}$ , and from the lower laser transition level 1 to the ground state 0,  $T_{10}$ , being much faster than the laser transition from level 2 to 1, we only need to take into account the population of the two intermediate levels 1 and 2, which form a two-level system. The population of the lower laser transition level then is always very small and can be set to zero. The two-level system interacts with  $N_{ph}$  photons inside a volume  $V$ . Photons of energy  $hf$  propagate inside the volume with the group velocity  $v_g$ . The interaction of the electromagnetic field and the amplifying medium with a density of active ions  $n_{at}$ , is condensed into the emission cross-section  $\sigma$ . Then, the equations for the population  $N_2$  of the excited state, and for the photon number  $N_{ph}$  are

$$\begin{aligned} \frac{d}{dt}N_2 &= -\frac{N_2}{\tau_L} - \frac{\sigma v_g}{V}N_2N_{ph} + R_p, \\ \frac{d}{dt}N_{ph} &= -\frac{N_{ph}}{\tau_p} + \frac{\sigma v_g}{V}N_2(N_{ph} + 1). \end{aligned} \quad (2.1)$$

The pump rate is given by  $R_p = I_p/I_{p,sat}\tau_L$  with the pump saturation intensity  $I_{p,sat}$ . Re-normalization to the inversion density  $w = n_{at}N_2$  and to laser intensity  $I = hfN_{ph}v_g/V$ , or to the experimentally accessible quantities amplitude gain  $g = \sigma v_g T_R w/2$  and optical power  $P = hfN_{ph}/T_R$  yields:

$$\begin{aligned}
\frac{d}{dt}w &= -\frac{w}{\tau_L} \left(1 + \frac{I}{I_{sat}}\right) + r_p, & \frac{d}{dt}g &= -\frac{g - g_0}{\tau_L} - \frac{gP}{P_{sat}\tau_L}, \\
\frac{d}{dt}I &= -\frac{I}{\tau_p} + \frac{\sigma v_g}{V} \frac{w}{n_{at}} (I + I_{sp}), & \frac{d}{dt}P &= -\frac{P}{\tau_p} + \frac{2g}{T_R} (P + P_{sp}).
\end{aligned} \tag{2.2}$$

with the quantities  $I_{sat} = hf/\sigma\tau_L$ ,  $P_{sat} = I_{sat}V/v_gT_R = I_{sat}A_{sat}$ ,  $I_{sp} = hf v_g/V$ ,  $P_{sp} = hf/T_R$ ,  $g_0 = \sigma\tau_L v_g T_R R_p/V$ ,  $\tau_p = T_R/2l$  being saturation intensity and power, spontaneously emitted intensity and power, small-signal gain, and cavity photon lifetime. The pump rate is substituted by the density-related quantity  $r_p = n_{at}R_p$ . Several situations will be discussed briefly, starting with the steady-state solution.

### Steady-state solution

In the following we neglect the spontaneous emission terms  $I_{sp}, P_{sp}$  in Eqs. (2.2). With  $d/dt = 0$ , the rate equations yield the steady-state values of inversion  $w_s$ , gain  $g_s$ , intensity  $I_s$  and power  $P_s$ :

$$w_s = \frac{\tau_L r_p}{1 + \frac{I_s}{I_{sat}}} = \frac{n_{at}V}{\sigma\tau_p v_g}, \quad g_s = \frac{g_0}{1 + \frac{P_s}{P_{sat}}} = l, \quad P_s = P_{sat} \left( \frac{g_0}{l} - 1 \right). \tag{2.3}$$

The first expression states that the steady-state inversion  $w_s$  is fixed at its threshold level, because the saturated gain  $g_s$  is pinned to the value of loss. The last expression is the well-known linear laser characteristic for the steady-state laser power  $P_s$ , with the threshold condition being  $g_0 = l$ .

### Excited state absorption

In general, higher levels than the upper lasing level will be present, which can be excited by the laser field if these levels occur at energies  $hf$  above the upper laser level. These transitions have a cross-section  $\sigma_{ESA}$ . Such excited state absorption (ESA) will reduce the stimulated emission into the laser mode, and increase the decay of the inversion in Eq. (2.1) leading to:

$$\begin{aligned}
\frac{d}{dt}N_2 &= -\frac{N_2}{\tau_L} - \frac{(\sigma + \sigma_{ESA})v_g}{V} N_2 N_{ph} + R_p, \\
\frac{d}{dt}N_{ph} &= -\frac{N_{ph}}{\tau_p} + \frac{(\sigma - \sigma_{ESA})v_g}{V} N_2 (N_{ph} + 1).
\end{aligned}$$

The effect of ESA can be included into Eqs. (2.2) and (2.3) by substituting

$$g_0 \rightarrow \frac{\sigma - \sigma_{ESA}}{\sigma} g_0, \quad P_{sat} \rightarrow \frac{\sigma}{\sigma + \sigma_{ESA}} P_{sat}. \tag{2.4}$$

ESA lowers both the small signal gain  $g_0$  and the saturation power  $P_{sat}$ .