Abstract (German)

Gegenstand dieser Arbeit ist die Beschreibung der zeitlich-räumlichen Pulsdynamik in Kerr-Linsen-modengekoppelten Lasern. Weiterhin wird ein neuartiges Konzept vorgeschlagen und theoretisch untersucht, um die Träger-Einhüllenden-Phase der von solchen Lasern erzeugten ultrakurzen Pulse elektronisch zu messen.

Erstmals wird in dieser Arbeit das Variationsprinzip zur näherungsweisen Lösung der zeitlich-räumlichen nichtlinearen Schrödingergleichung verwendet. Diese Gleichung beschreibt die Propagation eines Lichtpulses durch ein nichtlineares optisches Medium, auch Kerr-Medium genannt, wie es in Kerr-Linsen-modengekoppelten Lasern Anwendung findet. Die Pulsformung im Laser erfolgt hauptsächlich aufgrund der zeitlichen Dynamik, während die Pulsstabilisierung durch zusätzliche Ausnutzung von räumlichen Effekten erreicht wird. Eine exakte Lösung der Propagationsgleichung im Laser nimmt auf einem PC für einen Resonator mit Rotationssymmetrie mehrere Stunden in Anspruch, ansonsten noch wesentlich länger. Im Gegensatz dazu können die näherungsweisen Bewegungsgleichungen für einen Laserresonator in Sekundenschnelle gelöst werden. Bisherige auf dem Variationsprinzip basierende Gleichungen für die Pulspropagation im Laserresonator berücksichtigen nur die zeitliche Dynamik aufgrund von Dispersion und Selbstphasenmodulation. Im Gegensatz dazu ermöglicht die in dieser Arbeit entwickelte Beschreibung, welche auch Beugung und Selbstfokussierung beinhaltet, die Ermittlung sowohl der zeitlich-räumlichen Pulsform als auch des Parameterbereichs, in welchem modengekoppelter Betrieb möglich ist. Die Anwendung der hergeleiteteten Gleichungen wird anhand mehrerer Beispiele diskutiert. Die Gültigkeit der Näherung wird durch den Vergleich mit exakten numerischen Lösungen untersucht.

Weiterhin wird in dieser Arbeit ein neuartiges Konzept für die Detektion der Phase zwischen Träger und Einhüllender von ultrakurzen Lichtpulsen vorgeschlagen. Solche Verfahren sind wichtig, da für Pulse mit einer Dauer von nur wenigen optischen Zyklen viele Effekte nicht nur von der Pulsform abhängen, sondern auch vom unter der Einhüllenden oszillierenden optischen Trägerfeld. Zum Beispiel ist die Erzeugung hoher Harmonischer durch Fokussierung der Laserpulse auf ein Targetmaterial phasensensitiv. Elektronische Detektoren sind aufgrund ihrer Kompaktheit und der Einfachheit des Messaufbaus besonders attraktiv. Das in dieser Arbeit vorgeschlagene Prinzip beruht auf der Phasenabhängigeit der im Detektormedium durch Wechselwirkung mit dem Lichtpuls erzeugten Inversion. Bei Verwendung von Halbleitern können die ins Leitungsband angeregten Ladungsträger mittels einer angelegten Spannung abgesaugt werden und verursachen einen phasenabhängigen Strom im äußeren Stromkreis. Zuerst wird dieser Effekt anhand des Zwei-Niveau-Systems studiert. Anschließend wird die Untersuchung auf das Bänderschema von Halbleitern verallgemeinert. Für diesen Zweck werden Bandstrukturberechnungen für GaAs beziehungsweise InGaP durchgeführt. Die Berechnungen zeigen, dass ein messbarer Effekt zu erwarten ist, welcher durch Verwendung künstlicher Halbleiterstrukturen erhöht werden kann.

Chapter 1

Introduction

The invention of the laser heralded a new era in science, and has had widespread effects on everyday life and technology. In 1958, Schawlow and Townes proposed the concept of the laser [Sch58], and Maiman was the first to observe coherent radiation of visible light in ruby in 1960 [Mai60]. Since then, the laser has developed into an indispensable tool for research, and can be found in many everyday applications. As one of numerous scientific achievements related to the invention of the laser, new cooling techniques based on the interaction between atoms and coherent light became available. This recently paved the way for the generation of a new state of matter, the Bose-Einstein condensate, where all the atoms are in the same quantum state. Also a broad range of commercial applications are built on laser technology. The semiconductor laser can be found in CD players, laser pointers and numerous other everyday applications, and it is the backbone of optical communications. With hindsight, it is hardly conceivable that it took the inventors of the laser considerable effort to convince the patent lawyers of its use for communications [Tow99].

The advent of the mode-locked laser in 1964 [Har64], making ultrashort light pulses available, spawned a revolution on its own, with an enormous impact on many research fields and a huge potential for commercial applications. Here, pulsed operation is obtained by superimposing the individual laser modes at different frequencies, giving rise to a train of pulses. This is only possible if the modes maintain a fixed phase relationship, which is imposed by an additional coupling mechanism. While continuous wave lasers deliver a steady beam of coherent light concentrated in a narrow spectral range, mode-locked lasers can provide extremely short light pulses, with durations of two optical cycles or less. Since the pulse energies are concentrated in such a short time, high peak powers are obtained. For externally amplified systems, values on the order of Petawatts can be achieved. Ultrashort pulses exhibit broad coherent spectra, which can exceed an octave. The mode-locked laser opened new doors for many applications. The extremely short pulse durations are for example exploited in the new field of femtochemistry, enabling scientists to investigate and even control chemical reactions on the femtosecond time scale. Due to the high peak powers, new possibilities arise in material processing. The broad coherent spectrum is used for optical coherence tomography, a coherent imaging technique, enabling for example the examination of human retinal tissue in medicine.

Applications in ultra-high speed optical communications systems and networks are also in sight.

The concept of Kerr-lens mode-locking (KLM), which was discovered in 1991 [Spe91], proved especially successful. Here, the pulse formation is induced through the so-called Kerr effect, which gives rise to an intensity dependent focusing in the gain medium, resulting in an increased gain for pulsed operation. The predominantly used material for this type of laser is titanium doped sapphire, exhibiting a considerable Kerr nonlinearity and a broad spectral gain. With KLM lasers, few-cycle pulses and broad spectra can routinely be produced.

For few- to single-cycle pulses, effects become important which not only depend on the pulse envelope, but also on the phase between the rapidly oscillating carrier wave and the envelope. For a range of applications, this carrier-envelope (CE) phase must be detected and controlled. One example is the use of mode-locked lasers in frequency metrology, where the spectral lines are employed as a frequency ruler, and a change of the CE phase from pulse to pulse causes a frequency shift.

The scope of this thesis is twofold. By deriving approximate equations of motion in a KLM laser resonator, new insight is gained into the spatiotemporal pulse dynamics of such a laser, and into nonlinear pulse propagation in general. Furthermore, a new concept is proposed and theoretically investigated to electronically detect the CE phase of such ultrashort pulses.

In KLM lasers, the pulse shape is mainly determined by the temporal dynamics, while the pulse formation and stabilization is achieved through spatial effects. Solving the full propagation equations for a KLM laser resonator is a demanding numerical task. Already for a rotationally symmetric setup, it takes several hours to find the steady-state pulse shape, and otherwise even far longer. A simplified model, leading to a considerable reduction in computational effort, is needed to optimize the laser setup with respect to the many degrees of freedom. Furthermore, a basic model, taking into account only the most elementary effects, is helpful for a better understanding of the complex laser dynamics. In this thesis, such a model is developed, making an important contribution to the deeper understanding of the spatiotemporal dynamics in KLM lasers.

- Based on the variational principle, approximate equations of motion are derived for the propagation of Gaussian pulses through a nonlinear Kerr medium. In contrast to earlier work, which only took into account the temporal or spatial effects, this approximation includes for the first time the full spatiotemporal dynamics due to diffraction, dispersion and Kerr nonlinearity.

- The Gaussian result is compared to full numerical simulations for the propagation through a Kerr medium, and good agreement is found over a wide range of parameters. Even for extreme nonlinearities, where the Gaussian approximation does not yield quantitatively correct results, it still properly reflects the underlying physics.

- A simplified model of the KLM laser is developed. Within the Gaussian pulse approximation, the steady-state pulse solution can be obtained on a PC in seconds, as compared to several hours for full numerical simulations. The Gaussian and full numerical results are compared, yielding good agreement.

- As demonstrated in this thesis, based on the simplified dynamics it becomes possible to scan over a wide range of laser parameters, in order to identify the regime where pulsed operation is possible and to optimize the laser setup.
- The simplified model gives new insight into the laser dynamics. Especially, it is shown for the first time, that the spatiotemporal dynamics of modern KLM lasers is governed by the energy-conserving effects, and that gain and loss can be considered a perturbation to this dynamics.

The ultrashort pulses produced by KLM lasers consist of only few optical cycles. As pointed out above, in this regime effects become important which depend on the phase between the optical carrier and the envelope, necessitating methods to measure this CE phase. Of special interest are opto-electronic detectors based on solid-state effects, due to their compactness. This thesis makes valuable contributions to the CE phase sensitive dynamics of light-matter interaction, and investigates the application of these effects for CE phase detection.

- A new type of phase detector is proposed, which relies on the CE phase dependent inversion generated in a medium interacting with a few-cycle pulse.
- This effect is studied based on a two-level model. In this context, a new symmetry property is found, which motivates the introduction of a new parameter for characterizing the phase dependence of the inversion.
- The CE phase sensitivity of the inversion is studied in the weak field limit, revealing the difference between phase sensitive effects for optical and synthesized microwave pulses.
- Assuming a simple model pulse, and employing a special type of perturbation theory, analytical expressions are found for the phase dependence of the inversion. Furthermore, full numerical simulations are carried out.
- The discussion is extended to two-band semiconductors, showing that the phase sensitive effects are greatly reduced, as compared to a two-level system. The results are evaluated with regard to a CE phase detector.

The thesis is organized as follows:

In Chapter 2, the equations governing the optical pulse propagation in nonlinear media are presented at various levels of approximation, and the concept of the pulse envelope is introduced.

In Chapter 3, the variational principle is employed to derive approximate equations of motion, describing the propagation of Gaussian pulses through a nonlinear Kerr medium. The features and limitations of the Gaussian approximation are discussed, and the validity of the approximation is checked by comparison to exact numerical solutions over a wide parameter range.

In Chapter 4, a simplified model of the KLM laser is introduced. Based on the Gaussian approximation, the steady-state pulse solutions are extracted, and the stability properties of a typical laser setup are examined over a wide range of parameters. The Gaussian solutions are compared with full numerical simulations

In Chapter 5, the two-level system is presented as a basic model for light-matter interaction processes. The equations of motion for interaction of the system with an electromagnetic pulse are derived, and various physical effects are discussed.

In Chapter 6, the concept of CE phase detection based on the inversion in a two-level system is introduced. The finding of a special invariance property motivates the introduction of a new parameter, characterizing the CE phase dependence of the generated inversion. Based on the two-level dynamics in the weak field limit, the difference between excitation by optical and synthesized microwave pulses is discussed. Furthermore, analytical results are derived for the rectangular pulse as a basic model, and numerical simulations are performed. The discussion is extended to a two-band semiconductor, and the results are validated.

The results of the thesis are summarized in Chapter 7.

Chapter 2

Optical pulse propagation in nonlinear media

In the following, the equations governing the optical pulse propagation in nonlinear media are derived, largely following the discussion in [But90, Chapter 7]. This chapter is organized as follows: Section 2.1 presents the derivation of the optical wave equation from the fundamental equations governing classical electrodynamics. In Section 2.2, the relation between the electric field and the polarization induced in the propagation medium is established. Section 2.3 introduces the concept of field and polarization envelopes, which is in Section 2.4 applied to the nonlinear polarization terms. Section 2.5 contains the derivation of an approximate envelope propagation equation, assuming that the envelopes vary slowly as compared to the carrier. In Section 2.6, the discussion is extended to a superposition of several propagating fields, coupled together by nonlinear effects. Section 2.7 discusses the special case of propagation in a medium with intensity dependent refractive index. The chapter is summarized in Section 2.8.

2.1 Optical wave equation

Classical electrodynamics is governed by four fundamental equations, the Maxwell equations. In differential form, they are given by

$$\begin{aligned} \nabla \times \mathbf{E} &= -\dot{\mathbf{B}}, && \text{(2.1a)} \\ \nabla \times \mathbf{H} &= \mathbf{J} + \dot{\mathbf{D}}, && \text{(2.1b)} \\ \nabla \mathbf{D} &= \rho, && \text{(2.1c)} \\ \nabla \mathbf{B} &= 0, && \text{(2.1d)} \end{aligned}$$

where **E**, **H**, **B**, **D**, **J** and ρ are real functions of time t and position in three-dimensional space **r**. The overdot denotes a partial time derivative. The electric field **E**, the magnetic field **H**, the electric displacement **D**, the magnetic induction **B**, and the electric current density **J** are three-dimensional vectors; the charge density ρ is a scalar. In order to be self-consistent, the Maxwell