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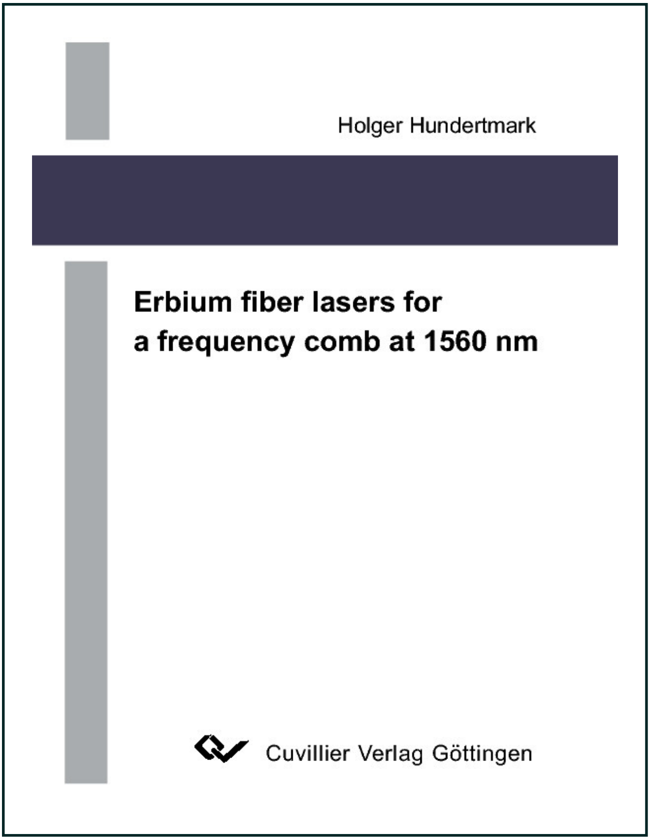
Erbium fiber lasers for a frequency comb at 1560 nm



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Chapter 1

Introduction

"*Higher, faster, wider*"
This statement does not only describe sports challenges, but can be also found in science. For science, it is less the struggling for new records, but more the aim of understanding the nature and discovering new areas and limits. One important scientific challenge aims at more precise definitions and measurements of fundamental constants. For the realization of a precise measurement, it is essential to have a suitable reference source and appropriate converters to different scales.

Up to now for instance, the definition of the second is given by a microwave atomic transition of the Cesium atom [Ude02b]. Until the end of the last century, complex and large frequency chains had to be realized for transferring the excellent stability and accuracy characteristics of the Cesium clock into the optical area for precise frequency measurements [e.g. Ude02b]. The connection of the radio frequency regime with the optical regime was simplified enormously by the employment of mode-locked ultra-short pulse laser systems showing a comb of discrete simultaneously oscillating waves at equally spaced optical frequencies. Hence, this comb can be totally characterized by only two radio frequencies, the pulse repetition rate spacing the frequencies in the Fourier space and the carrier-envelope-offset frequency defining the offset concerning the "zero frequency" [Tel99, Ude02a].

The implementation of frequency combs based on ultra-short pulse laser systems has been simplified by the development of highly nonlinear fibers, like photonic crystal fibers (PCF) or tapered fibers [Wad02]. Whereas the pulse repetition rate can be detected directly, the carrier-envelope-offset frequency has to be measured indirectly. The common measurement scheme is based on the self-referencing method [e.g. Tel99, Ude02a], where a comb structured octave-broad optical spectrum is necessary. As ultra-short pulsed laser systems typically do not emit an octave-broad optical spectrum, the required bandwidth can be achieved by nonlinear spectral broadening of the ultra-short laser output pulses in the above mentioned nonlinear fibers.

Titanium-Sapphire lasers operating around 800 nm were the first light sources used for the experimental realization and application of an optical frequency comb. The stability transfer of a Cesium clock on the comb parameters of a Titanium-Sapphire laser enabled the precise measurement of optical transitions down to uncertainties of only a few Hz, for e.g. Calcium [Ste01b, Sch03], Ytterbium [Ste01c, Sch03] or Hydrogen [Nie00]. Furthermore, the coupling of the radio frequency regime with the optical regime allows the stabilization of the frequency comb. This results in a stabilization of every optical frequency, which allows the use of these lines themselves as stable optical reference frequencies [e.g. Cun03]. In general, it has been demonstrated, that frequency combs based on ultra-short pulse laser systems can not only be used for metrology applications, but also for a large variety of applications in the field of applied and fundamental physics, like efficient nonlinear optics [e.g. Kie02, Cun03] or timing synchronization of mode-locked lasers [e.g. Cun03].

Recently, passively mode-locked fiber-based oscillators have gained more interest, since they are more compact and reliable light sources than bulky Titanium-Sapphire laser systems. Especially sub-100 fs Erbium-doped fiber lasers operating around 1560 nm are ideal candidates for a frequency comb, as they can be realized easily using commercially available fibers and fiber-based components. Furthermore, they allow the transfer of the frequency comb technology into the important telecommunication wavelength area around 1560 nm, which is typically not covered by frequency combs based on Titanium-Sapphire laser systems. As the pulse energy of several 100 pJ from passively mode-locked Erbium fiber oscillators is usually too low for the generation of the required octave-broad optical spectrum, the oscillator pulses have to be amplified. It was shown, that a pulse energy of 1 nJ to 2 nJ is sufficient for the generation of a coherent octave-spanning supercontinuum in silica-based nonlinear fibers [e.g. Tau03, Was04a, Sch04].

For the stabilization of the repetition rate and of the carrier-envelope-offset frequency regarding to a radio frequency reference source, it is essential, that technical influences on the comb parameter - like the environmental temperature or the pump power - are known and that their control limits are investigated. A laser system used as a light source for a optical frequency comb should provide at least two inputs for controlling both comb frequencies independently.

In this work, an all-fiber passively mode-locked Erbium-doped oscillator-amplifier system was realized, investigated and used for spectral broadening in nonlinear fibers with respect to its suitability as a light source for a frequency comb at 1560 nm. In contrast to comparable experiments on Erbium fiber lasers applying a dispersion-shifted silica glass based nonlinear fiber [Tau03, Was04a, Sch04], two different kinds of photonic crystal fibers showing a higher effective nonlinearity than the above mentioned fibers are used for the generation of the supercontinuum. Influences on the oscillator's comb parameter were analyzed and a stabilization of the corresponding frequencies was evaluated and demonstrated.

This dissertation is structured as follows:
In chapter 2, the set-up and the characterization of a passively mode-locked all-fiber Erbium oscillator-amplifier system is presented emitting less than 85 fs laser pulses with a pulse energy of 1 nJ at 1560 nm. The extracted laser pulses are applied for the generation of a supercontinuum in two highly nonlinear photonic crystal fibers, one fiber based on fused silica glass and the second based on SF6 glass. An octave-spanning supercontinuum generation in the photonic crystal fiber made out of SF6 glass is demonstrated enabling the opportunity for measurements of the carrier-envelope-offset frequency.
In chapter 3, technical influences acting on the repetition rate of the all-fiber oscillator are investigated. A highly sensitive measurement setup is implemented allowing the observation of fast repetition rate changes and their resulting pulse-to-pulse timing fluctuations. The pump power influence is applied to realize the first reported phase-lock of a fiber oscillator's repetition rate with respect to a Hydrogen maser as the reference source. Additionally, a modified Erbium fiber oscillator setup is realized providing an enhanced control range of the repetition rate. The improved setup enables the tuning of the repetition rate by nearly ± 1 % being the largest reported tuning range for a passively mode-locked Erbium fiber laser.
In chapter 4, the first and up to now the unique measurement of the carrier-envelope-offset frequency based on a supercontinuum generated in a SF6 photonic crystal fiber is demonstrated. A simplified detection setup is established applying the output signal of the all-fiber oscillator directly for the detection of the carrier-envelope-offset frequency. A phase-lock of the carrier-envelope-offset frequency is realized by using the pump power as the control element resulting in residual carrier-envelope-offset frequency fluctuations of less than 1 Hz.
Finally, in chapter 5, the results of this work are summarized and a short outlook for future investigations is given.

Chapter 2

Supercontinuum generation with an Erbium-doped fiber oscillator-amplifier system

The generation and investigation of a spectral supercontinuum with fs laser systems is a growing research area in fundamental and applied physics. The supercontinua mainly generated by fs laser pulses are increasingly used in frequency metrology, e.g. for frequency comb generation [e.g. Tel99, Hol00, Jon00a], or for optical coherence tomography [Har01, Biz03].

A highly nonlinear fiber with a special dispersion characteristic and with a small core enables a simple realization of a broad optical spectrum with pulses having a pulse energy in the nanojoule-range [e.g. Rus03]. The dispersion characteristics of such fibers lead to a retaining or shortening of the launched pulse duration and the small core lead to a high pulse intensity resulting in an efficient spectral broadening caused by nonlinear effects. This is mainly achieved by setting the zero dispersion point around the central wavelength of the pulse or on a lower value. In recent years, several developments of new fiber types have been reported showing a significant higher nonlinearity compared to standard single-mode fibers. The nonlinear coefficient γ of a fiber is defined by the following equation [Sha04]:

$$\gamma = \frac{2 \cdot \pi}{\lambda} \cdot \frac{n_2}{A_{eff}} \tag{2.1}$$

A higher nonlinear refractive index (n_2) or a smaller effective mode area of the fiber (A_{eff}) is required to increase of the higher nonlinear coefficient (γ) at a given wavelength (λ).

One approach to design a highly nonlinear fiber is a dispersion-shifted fiber, which is co-doped with e.g. Germanium for an increase of the nonlinear refractive index and which has a smaller core diameter [Nis01, Nic03]. The second highly nonlinear fiber type is based on tapered silica glass fibers [Bir00, Wad02]. By reducing the core diameter of the fiber, not only the intensity of a propagating signal increases, but also the zero dispersion point of the fiber can be shifted to shorter wavelength dependent on the diameter of the taper [Har02]. The third fiber type is the photonic crystal fiber (PCF) [Rus03], whose design enables a small core and an enhanced control of the dispersion characteristics, especially of the zero dispersion wavelength and the slope of the dispersion around this wavelength [Wad02]. PCF are mainly made of silica glass, but during the last years, other glass materials with a higher nonlinear refractive index, like SF57 [Kia02, Pet03], SF6 [Rav02], bismuth [Ebe04, Gop04] or telluride glasses [Rav03] have been investigated. For example, a bismuth fiber with a nonlinear coefficient of more than $1000\cdot(\mathrm{W\cdot km})^{-1}$ was realized being about three orders of magnitude higher than the value of the telecommunication standard fiber SMF 28 ($\gamma_{SMF\ 28} \sim 1\cdot(\mathrm{W\cdot km})^{-1}$) [Ebe04].

Most of the research on supercontinua generated by fs laser pulses in PCF has been performed with Titanium-Sapphire laser systems operating around 800 nm. These systems deliver high energy laser pulses of several nanojoule and pulses shorter than 100 fs enabling an efficient and simple generation of supercontinua [e.g. Nol99, Kor03, Ser04, Hav04]. As Titanium-Sapphire laser systems only cover the wavelength region around 800 nm, alternatively sub-100 fs ultra-short pulse laser systems have been investigated for the generation of supercontinua, like a Chromium-Forsterite laser [Nau02, Tho03], an optical parametric amplifier [Fed02] or an Erbium fiber laser [Tau03].

Recently, Erbium-doped fiber lasers operating around 1560 nm have gained more importance as compact and reliable diode-pumped light sources for the generation of supercontinua with the main purpose to employ them as light sources for a frequency comb [Tau03, Yam03, Nic03, Nic04]. These oscillators are based on commercially available fiber components and allow the generation of ultra-short pulses with durations down to 55 fs [Rot03]. By taking advantage of nonlinear effects, an all-fiber 34 fs amplifier system was demonstrated [Nic04]. The pulse energy of a typical Erbium fiber oscillator is about several hundreds of picojoule enabling a spectral broadening in a nonlinear fiber. On the other hand, for the purpose of the realization of a frequency comb based on an Erbium fiber oscillator, this pulse energy is usually too low, as it should be in the nanojoule-range for the required octave-spanning supercontinuum generation. By this, an amplifier stage for increasing the pulse energy into this pulse energy range is essential. Several suitable fiber-based amplifiers were demonstrated for this purpose. They showed a pulse energy of 8 nJ at the full oscillator's repetition rate of 46 MHz [Nic04] or of several 100 nJ up to the microjoule-regime with a reduced repetition rate around 200 kHz [Ade04, Ime04]. The generation of widely broadened supercontinua using Erbium fiber laser systems has mainly been demonstrated in silica-based highly nonlinear fibers with a zero group velocity dispersion wavelength close to 1500 nm [Tau03, Nic03, Nic04].

In this chapter, the generation of a supercontinuum in two different kinds of PCF with an all-fiber 1 nJ and sub-85 fs oscillator-amplifier system is presented. The first fiber type investigated is a commercially available silica-glass PCF with a zero dispersion wavelength around 1560 nm. The second fiber is a prototype PCF based on SF6 glass and a zero dispersion group velocity around 1.3 µm made by the Optoelectronics Group at the University of Bath.

2.1. Passively mode-locked Erbium fiber lasers

For the generation of ultra-short pulses in the femtosecond-regime, a broad optical laser output spectrum is essential. This broad spectrum is required, as for the realization of these pulse durations, the Fourier uncertainty given by the scalar product of the laser's frequency bandwidth $\Delta\nu$ and the pulse duration $\Delta\tau_{Pulse}$ has to be equal or larger than a constant *a* given by the spectral and temporal shape of the pulse. For example, the constant *a* is 0.441 for a Gaussian shaped pulse [Die96].

$$\Delta\nu \cdot \Delta\tau_{Pulse} \geq a \qquad (2.2)$$

The common method for the generation of femto-second laser pulses is mode-locking. As postulated above, the active medium and the used cavity have to provide a broad spectral gain for simultaneous oscillating of multiple cavity eigenmodes. These modes have to be phase-locked with a constant phase difference $\Delta\varphi$, ideally $\Delta\varphi = 0$, between each other resulting in the generation of an ultra-short pulse with high intensity. In Fig. 2.1, the superposition of eight oscillating cavity eigenmodes with a random phase relation (top) and with a fixed phase relation of $\Delta\varphi = 0$ (bottom) are shown.

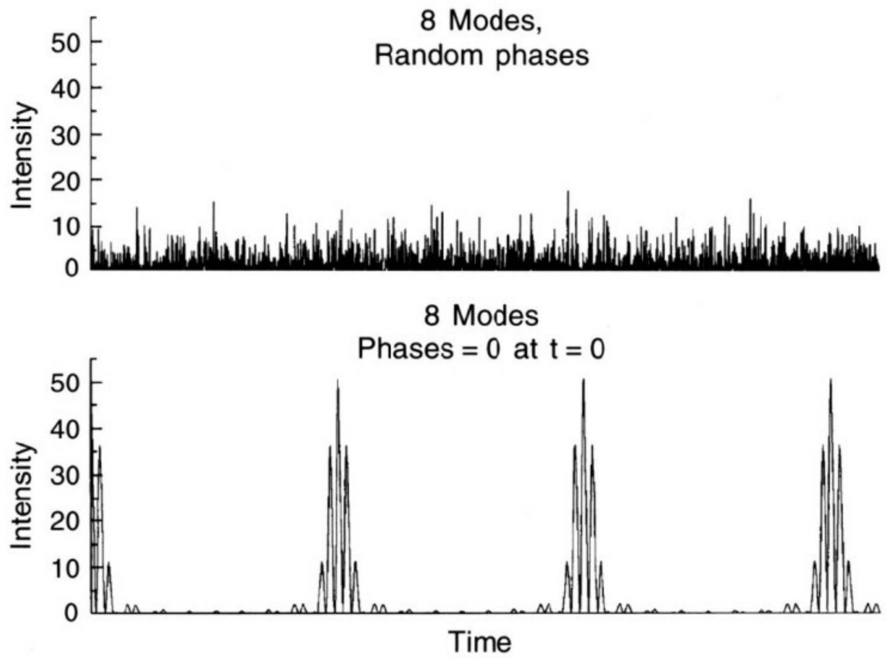

Fig. 2.1: Output signal generated by 8 modes with random phase relation (top) und constant phase relation (bottom) (taken from [Tre03])

A random phase relation between the cavity modes leads to a noisy low intense time signal. The signal of different modes with constant locked phases - $\Delta\varphi = 0$ - results in the generation of pulses caused by constructive interference of the electro-magnetic field for short time scales and destructive interference on long time scales between the pulses. A mathematical description of the mode-locking mechanism can be found elsewhere [Ber93, Kne95].

The locking of the phases of the laser modes in fibers can be achieved actively and passively. Whereas the active mode-locking mechanism requires a modulator, whose modulation frequency has to correspond to the fundamental or a harmonic of the spacing of the cavity eigenmodes [Kne95], the passive mode-locking is achieved by the propagating signal itself as a result of nonlinear effects.

In general, the phase-coupling of the cavity eigenmodes is realized by a modulation of the phase or the amplitude leading to the generation of frequency sidebands of the modulated carrier frequency. The sidebands may be sustained, if they correspond with the eigenmodes of the cavity. The modulated sidebands generate further sidebands themselves and consequently, the optical spectrum becomes broader. This broadening process stops, when the losses for new generated sidebands exceed the gain provided by the active gain medium or by nonlinear effects.

Usually, passively mode-locking mechanisms allow the generation of laser pulses down to the femto-second regime compared to the laser systems based on active mode-locking emitting mainly pulses in the pico-second regime [Ser04]. For example, passively mode-locked Titanium-Sapphire lasers allow the generation of pulses with a duration significantly below 10 fs [Sut99, Mor99].

The mechanisms for passively mode-locking are based mainly on nonlinear effects , like the nonlinear absorption and, especially, the nonlinear refractive index [e.g. Ber93, Agr01]. The nonlinear refractive index is induced by the third order susceptibility $\chi^{(3)}$ of a medium and results in the intensity dependence of the refractive index $n(\omega,I)$ [e.g. Ber93, Sut96]:

$$n(\omega,I) = n_o(\omega) + \frac{3 \cdot \mathrm{Re}\{\chi^{(3)}\}}{8 \cdot n_0(\omega)} \cdot I(t) = n_o(\omega) + n_2 \cdot I(t)\,. \tag{2.3}$$

In equation (2.3), $n_0(\omega)$ is the linear refractive index depending on the frequency ω, $I(t)$ the intensity of the propagating signal and n_2 the nonlinear coefficient based on the third order susceptibility. The response time of this nonlinear effect in optical fibers is less than ten femto-seconds [Boy98, Sie99]. In combination with a strong amplitude or phase modulation leading to a broad optical spectrum, this ultra-short response time is also essential for the generation of pulses shorter than 100 fs.