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Erbium fiber lasers for a frequency comb at 1560 nm

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Abstract

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Frequency combs based on ultra-short pulse laser systems present a versatile clockwork for the physical link between radio frequencies and optical frequencies. The characterization of the optical output spectrum of a laser by two radio frequencies - the pulse repetition rate and the carrier-envelope-offset frequency - has opened up new opportunities for precision applications in contrast to conventional methods realized by complex frequency chains. The frequency stability transfer of radio frequency or optical reference sources on the comb and vice versa allows a large variety of powerful experiments in the field of applied and fundamental physics.

In this work, a passively mode-locked all-fiber Erbium oscillator-amplifier system was realized and characterized concerning its suitability as a light source for a frequency comb around the telecommunication wavelength at 1560 nm. Influences on both comb frequencies were analyzed and a parameter control for the stabilization of each frequency was evaluated.

The detection method of the comb parameters based on self-referencing demands a coherent octave-broad supercontinuum, which can be generated in highly nonlinear fibers, like photonic crystal fibers. With the oscillator-amplifier system, the spectral broadening around 1560 nm in a silica glass and a SF6 glass based photonic crystal fiber was investigated. The higher effective nonlinearity of the SF6 fiber enabled the generation of a more than octave-spanning supercontinuum from 400 nm to 2000 nm with the lowest reported pulse energy from an Erbium fiber-based system so far.

The dependence of the pulse repetition rate on the environmental temperature and the oscillator's pump power was investigated. A sensitive measurement scheme allowed the online detection of repetition rate changes of the free-running oscillator. For the first time, the pump power of a passively mode-locked Erbium fiber laser was used as a control element for a phase-lock to reduce the repetition rate fluctuations close to the frequency stability of the used Hydrogen maser reference. Furthermore, a modified passively mode-locked Erbium fiber oscillator was demonstrated showing a repetition rate of 55 MHz and a wide tuning range of the repetition rate of ± 1 % corresponding to 1.1 MHz being the largest reported value for comparable systems.

For the first time, the carrier-envelope-offset frequency was measured via the octave-broad supercontinuum generation in a highly nonlinear SF6 fiber. The observed bandwidth as a measure of phase fluctuations of this comb parameter was less than 50 kHz. This is less than a fourth compared to the minimum ever achieved before for a passively mode-locked Erbium fiber laser. Using the pump power as the control input, the carrier-envelope-offset frequency was phase-locked to a quartz oscillator resulting in residual frequency fluctuations of less than 1 Hz.

In consequence, the results demonstrate the suitability of a passively mode-locked Erbium fiber laser in combination with a highly nonlinear photonic crystal fiber for the realization of a frequency comb around 1560 nm.

Key Words: Erbium fiber laser, supercontinuum, frequency comb

Zusammenfassung

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Erbium-Faserlaser für einen Frequenzkamm bei 1560 nm

Auf Ultrakurzpuls-Lasersystemen basierende Frequenzkämme repräsentieren vielseitige Transferuhrwerke für die physikalische Verknüpfung des Radiofrequenzbereiches und des optischen Bereiches. Die Charakterisierung des Laserausgangsspektrums durch die Pulswiederholrate und die Schlupffrequenz, die beide im Radiofrequenzbereich liegen, hat viele neue Anwendungsfelder im Bereich der Präzisionsanwendungen im Vergleich zu herkömmlichen Verfahren auf Basis von komplexen Frequenzketten erschlossen. Der Stabilitätstransfer eines Radiofrequenz- oder eines optischen Referenzsignals auf den Frequenzkamm ermöglicht eine Vielzahl an zielführenden Experimenten für die angewandte und grundlagenorientierte Physik.

In der vorliegenden Arbeit wurde ein rein faseroptisches passiv modengekoppeltes Erbium-dotiertes Oszillator-Verstärker-System hinsichtlich der Einsatzfähigkeit als Lichtquelle für einen Frequenzkamm im Telekommunikationswellenlängenbereich um 1560 nm realisiert und charakterisiert. Einflüsse auf Pulswiederholrate und Schlupffrequenz wurden analysiert und eine Parameterkontrolle für eine Stabilisierung der jeweiligen Kammfrequenzen evaluiert.

Die Bestimmung der Kammparameter mittels Selbst-Referenzierung setzt ein kohärentes oktav-breites Superkontinuum voraus, was in hoch-nichtlinearen Fasern, wie z.B. photonischen Kristallfasern, erzeugt werden kann. Mit dem Oszillator-Verstärker System wurde die spektrale Verbreiterung in einer aus Quarz- und in einer aus SF6-Glas hergestellten photonischen Kristallfaser um 1560 nm vergleichend untersucht. Die höhere Nichtlinearität der SF6-Faser ermöglichte die Erzeugung eines mehr als eine Oktave breiten Superkontinuums von 400 nm bis 2000 nm mit der bislang geringsten dokumentierten Pulsenergie eines faserbasierten Erbiumsystems.

Die Abhängigkeit der Pulswiederholrate von der Umgebungstemperatur und der Oszillatorpumpleistung wurde untersucht. Ein sensitiver Messaufbau ermöglichte die direkte Messung von Repetitionsratenschwankungen des unstabilisierten Oszillators. Die Pumpleistung des passiv modengekoppelten Erbium-Faserlasers wurde erstmalig eingesetzt, um die Repetitionsratenfluktuationen nahezu auf das Stabilitätsniveau eines als Referenz genutzten Wasserstoff-Masers zu reduzieren. Darüber hinaus wurde ein modifizierter passiv modengekoppelter Erbium-Faser-Oszillator mit einer Repetitionsrate von 55 MHz realisiert, die sich um ± 1 % bzw. 1.1 MHz verändern ließ, was bis jetzt den größten dokumentierten Wert für derartige Systeme darstellt.

Die Schlupffrequenz wurde erstmalig mittels der Erzeugung eines oktaven-breiten Spektrums in einer hoch nichtlinearen SF6-Faser gemessen. Die detektierte Bandbreite, welche ein Maß für das Phasenrauschen dieser Kammfrequenz ist, war kleiner als 50 kHz. Dieses ist weniger als ein Viertel des bisherig erreichten Minimalwertes für einen passiv modengekoppelten Erbium-Faserlaser. Die Pumpleistung wurde als Stellelement verwendet, um die Schlupffrequenz mit Hilfe eines Quarzoszillators derart zu stabilisieren, dass die verbleibenden Restfrequenzschwankungen kleiner als 1 Hz zu waren.

Mit diesen Ergebnissen wurde die Eignung des passiv modengekoppelten Faserlasers in Kombination mit einer hoch nichtlinearen photonischen Kristallfaser für die Realisierung eines Frequenzkammes um 1560 nm gezeigt.

Schlagwörter: Erbium-Faserlaser, Superkontinuum, Frequenzkamm

Contents

List of abbreviations

EDFA	Erbium-doped fiber amplifier
f_{CEO}	Carrier-envelope-offset frequency
f_{Rep}	Repetition rate
FROG	Frequency resolved optical gating
FWHM	Full-width-half-maximum
FWM	Four-wave-mixing
GVD	Group velocity dispersion
NLPR	Nonlinear polarization rotation
NSR	Non-solitonic radiation
OSA	Optical spectrum analyzer
P-APM	Polarization additive-pulse-mode-locking
PBS	Polarization beam splitter
PCF	Photonic crystal fiber
PLL	Phase-locked loop
RFSA	Radio frequency spectrum analyzer
SHG	Second harmonic generation
SPIDER	Spectral phase interferometry for direct electric-field reconstruction
SPM	Self-phase modulation
THG	Third harmonic generation
TOD	Third order dispersion
VCO	Voltage-controlled oscillator
WDM	Wavelength-division-multiplexer
XPM	Cross-phase modulation

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.