Coherent octave-spanning supercontinuum generation in a SF6-fiber for a frequency comb around 1560 nm

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Abstract: We report the octave-broad supercontinuum generation in an extruded SF6-PCF with an Erbium fiber laser oscillator-amplifier system around 1560 nm. The oscillator's carrier-envelope-offset-frequency was measured in a modified f-2f-interferometer and phase-locked to an external reference source by pump power control.

1. Introduction

The generation of a supercontinuum with femtosecond (fs) laser pulses in photonic crystal fibers has opened up new opportunities in frequency metrology, especially for the realization of fs laser based frequency combs [1-3]. Most of the research on octave-broad supercontinuum generation for frequency combs has been performed with Ti:Sapphire laser systems operating around 800 nm. Recently Er-doped fiber oscillator-amplifier systems around 1560 nm have gained more importance as light sources for octave-broad supercontinuum generation [4,5], since they are compact and reliable diode-pumped laser systems. Until now, the generation of widely broadened supercontinua using these fiber-based laser sources has been mainly achieved in silica-based highly nonlinear fibers with a zero group velocity dispersion around 1500 nm. With silica-based nonlinear fibers, it is still necessary to use fiber lengths of several meters or launched laser pulses with more than one nJ pulse energy for the octave-broad supercontinuum generation and subsequently for the realization of a frequency comb.

A frequency comb is characterized by two radio frequencies: the repetition rate f_{Rep} and the carrier-envelope-offset frequency f_{CEO}. As the f_{Rep} can be directly detected with a photo diode and a radio-frequency (RF) spectrum analyzer, the measurement of the f_{CEO} is more complex. The common method ("self-referencing" e.g. [1]) requires a coherent octave-spanning supercontinuum and an f-2f-interferometer: In this interferometer the long-wavelength components of the octave-spanning supercontinuum are frequency-doubled and superimposed onto the short-wavelength components on a photo-detector and the resulting f_{CEO}-beat can be detected and analyzed with an RF spectrum analyzer. In the last year not only the Erbium fiber oscillator's f_{CEO} was measured [4], but also the stabilization of both comb parameter was demonstrated by [6] by using silica-based fibers for the supercontinuum generation.

In this contribution we present the supercontinuum generation from 400 nm to beyond 1750 nm in a 30 cm long extruded PCF made out of SF6 [7], which shows a higher nonlinear coefficient than fused silica, with only 200 pJ launched laser pulses from an passively mode-locked Erbium oscillator-amplifier system. The generated more than octave-spanning supercontinuum allowed the realization of a simplified f-2f-interferometer, where the frequency-doubled signal of the fiber oscillator was superimposed onto the corresponding spectral part of the supercontinuum. Furthermore, we used an electronic feedback loop for controlling the oscillator's pump power and subsequently for stabilization of f_{CEO}.

2. Experimental setup and results

The schematic setup for the generation of an octave-broad supercontinuum and the detection scheme of the carrier-envelope-offset frequency is shown in Fig. 1. The Erbium fiber oscillator was passively mode-locked by nonlinear polarization rotation [8] and delivered an output power of 14 mW at a repetition rate of 59.1 MHz. The extracted laser pulses were compressible in a fiber arrangement down to an interferometric autocorrelation width of 90 fs resulting in a pulse duration of 64 fs assuming a Gaussian pulse shape.

The output signal of the oscillator was split by a 50/50-coupler for seeding both arms of the f-2f-interferometer – the arm for the supercontinuum generation and the arm for second-harmonic generation – with an average power of 7 mW.

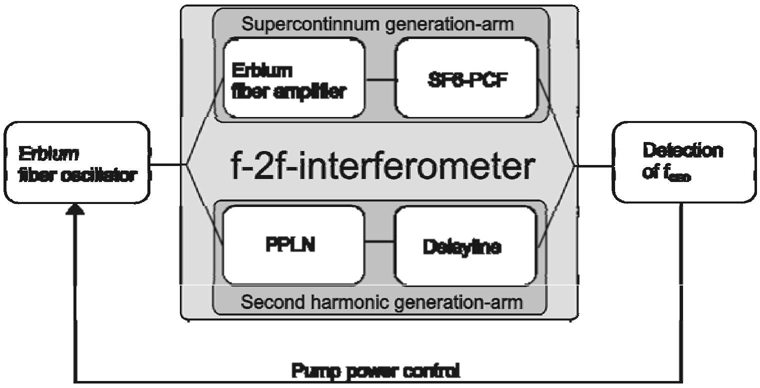

Fig. 1. Schematic of measurement setup

In the supercontinuum generation arm of the f-2f-interferometer the oscillator pulses were amplified to 59 mW in an Erbium-doped fiber and compressed down by a fiber arrangement to an interferometric autocorrelation width of 85 fs, which resulted in a pulse duration of 60 fs assuming a Gaussian shape. These amplified pulses were launched into a 30 cm long extruded SF6-PCF with a core diameter of 2.6 µm and zero group velocity dispersion around 1.3 µm for the generation of the supercontinuum [7]. With a coupling efficiency of about 20 % a launched average power up to 12.5 mW was measured after the PCF, corresponding to a pulse energy of about 210 pJ at 1560 nm. The spectrum after the PCF was detected with an optical spectrum analyzer (OSA) operating between 350 nm and 1750 nm.

Fig. 2 shows the generated supercontinuum for the maximal launched pulse energy of 210 pJ. The spectrum spanned over an octave from 750 nm to 1750 nm with two major peaks around 800 nm and 1550 nm. Furthermore, separated spectral peaks existed around 400 nm and 600 nm, so that the generated supercontinuum extended unevenly from 400 nm to beyond 1750 nm. Since the supercontinuum showed an intensive peak around 800 nm this spectral area was selected for the measurement of f_{CEO}.

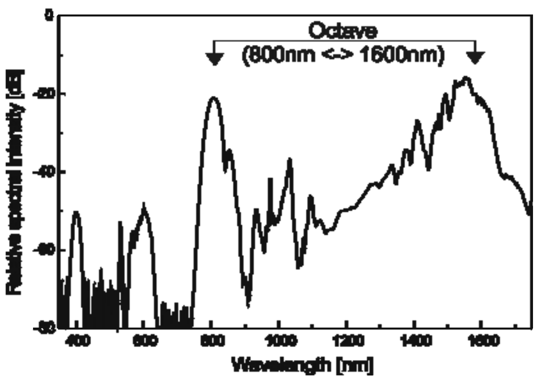

Fig. 2. Supercontinuum generated in 30 cm long SF6-PCF with 210 pJ launched laser pulses at 1560 nm

In the second-harmonic generation arm the laser pulses were compressed by a fiber arrangement and focussed into a periodically-poled Lithium-Niobate crystal (PPLN) with a domain period of 20.4 µm for second harmonic generation to around 800 nm. The collimated second harmonic signal propagated through a delay line comprising a sigma path for adjustment of the time delay between the two arms and for proper linear polarization of the laser pulses around 800 nm. This linearly polarized signal was superimposed onto the signal from the supercontinuum generation arm on a 50/50-beam splitter. The resulting f_{CEO}-beat was detected with a silicon photodiode and amplified before it was observed with an RF spectrum analyzer.

In Fig. 3 a typical scan from 0 MHz to 60 MHz is shown at a resolution bandwidth of 51 kHz. The measured beats of the f_{CEO} were 35 dB above the noise floor at a frequency of 13.2 MHz and 45.9 MHz and the intensive peak at a frequency of 59.1 MHz represents the oscillator's repetition rate.

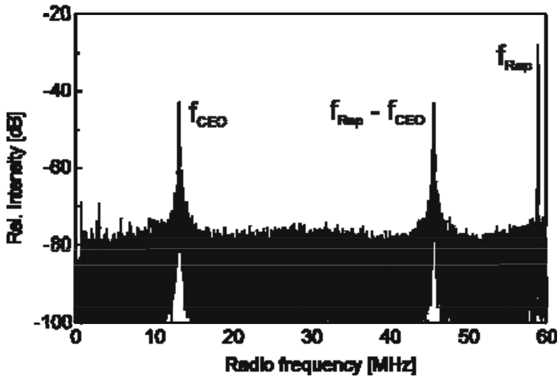

Fig. 3. Radio-frequency measurement of the carrier-envelope-offset frequency (13.2 MHz and 45.9 MHz) and the repetition rate (59.1 MHz) at a resolution bandwidth of 51 kHz

The f_{CEO}-beat was influenced by the pump power and showed a linear dependence of about 2 MHz/mW. Therefore, the pump power was controllable with an electronic feedback loop for the stabilization of the f_{CEO}. In this loop the electrical signal was pre-filtered by a band pass filter and amplified before it was filtered by a phase-locked loop tracking oscillator. The tracked signal was divided by a binary divider in order to reduce the required locking bandwidth and the output signal was phase-compared with a RF reference signal in a double balanced mixer. The resulting error signal was amplified in a low frequency loop amplifier and used for controlling the pump power of the fiber oscillator. With division factors down to a value of 8 a long-term phase-lock of the f_{CEO} was demonstrated reducing the residual frequency fluctuations to fractions of one Hertz.

3. Summary

We reported on the octave-broad supercontinuum generation from 400 nm to beyond 1750 nm in a 30 cm long extruded SF6 photonic crystal fiber with about 200 pJ laser pulses from a diode-pumped Er-doped all-fiber oscillator-amplifier system. In comparison to experiments on fs supercontinuum generation with passively mode-locked Er-doped fiber laser systems using silica-based nonlinear fibers, the use of the extruded SF6 fiber enabled the generation of a broader supercontinuum, containing also visible components, with a low pulse energy of less than one nJ and a fiber length less than one meter. The more than octave-broad supercontinuum enabled the measurement of the carrier-envelope-offset frequency, f_{CEO}, of the oscillator's frequency comb in a modified f-to-2f-interferometer superimposing the frequency-doubled output from the oscillator onto the generated supercontinuum. Using the fiber oscillator's pump power as control input, a phase-lock of the f_{CEO} to an external radio frequency reference was demonstrated.

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4. References

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