Picosecond pulses from wavelength swept continuous-wave Fourier domain mode locked lasers

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Abstract

Ultrafast lasers play a crucial role in many fields of science, however, up to now, high energy pulses directly from compact, efficient and low power semiconductor lasers are not available. Therefore we introduce a new approach based on temporal compression of the continuous-wave, wavelength swept output of Fourier domain mode locked lasers, where a narrowband optical filter is tuned synchronously to the roundtrip time of light in a kilometre long laser cavity. So far, these rapidly swept lasers enabled orders of magnitude speed increase in optical coherence tomography. Here, we report on the generation of ~60-70ps pulses at 390kHz repetition rate. Since energy is stored optically in the long fibre delay line and not as population inversion in the laser gain medium, high energy pulses can now be generated directly from a low power, compact semiconductor based oscillator. Our theory predicts sub-ps pulses with this new technique in the future.

Introduction

Compact and reliable ultrashort-pulse, high energy laser sources[1] are of great importance for many fields in science and engineering like material processing, biomedical optics or optical communication. Compared to other gain media the application of fully semiconductor based laser sources can have many significant advantages due to optimal compactness, robustness, cost-effectiveness, very high wall-plug efficiency, simple current pumping, broadband gain bandwidth or spectral versatility. Since their first demonstration[2], there has been great effort to improve the performance of ultrashort pulse generation with semiconductor lasers reducing the pulse duration and increasing output power[3,4]. Active, passive or colliding pulse mode-locking techniques[5,6] were the prerequisite for the generation of few ps and sub-ps pulses, considerably impeded due to nonlinear phase changes associated with gain saturation[4]. So far, shortest pulse durations from semiconductor lasers, reaching several tens of fs, have been demonstrated with optically pumped passively mode-locked vertical-external-cavity surface emitting lasers (VECSEL)[7] based on wideband semiconductor saturable absorber mirrors (SESAM)[8].

However, a drawback of conventional mode-locked, q-switched or gain switched semiconductor lasers systems are the comparably low pulse energies, as a direct consequence of the short carrier relaxation time (~100ps), high gain and low saturation energy in the semiconductor gain medium[4,5,9]. A major problem is that short carrier relaxation times in the semiconductor gain media impede the realization of low repetition rate mode-locked systems. Thus, semiconductor lasers with higher pulse energies have very high levels of average output power, making them impracticable for many applications where compact, low power light sources without extensive infrastructure are desired. Generally, pulse energy can be increased using semiconductor based master oscillator power amplifier (MOPA) systems. Whereas in case of single spatial mode semiconductor optical amplifiers (SOA) the achievable pulse energies typically range from a few pJ to few tens of pJ[3,9], higher energies become feasible using multispatial mode semiconductor based amplifiers like inverse bowtie SOAs[10] or tapered amplifiers[11-14]. Increased pulse energies can be achieved using the semiconductor based eXtreme chirped pulse amplification (X-CPA) concept[9] where pulses are stretched temporally prior to amplification and the output energy of the recompressed pulse then exceeds the fundamental energy storage limit of the semiconductor gain medium. Besides edge emitting diodes, ultrashort pulses can be generated with optically pumped passively mode-locked VECSELs[15] exhibiting increased saturation power and thus allowing for comparably high average output powers and pulse energies[16]. However, disadvantages of optical pumping can be, especially at high average power, a lower wall-plug efficiency and the need for a more sophisticated thermal management. In this work, we introduce and investigate a fundamentally new concept of short pulse generation based on Fourier domain mode locked (FDML) lasers[17,18], a recently introduced novel type of rapidly wavelength swept lasers. Whereas ps or sub-ps pulses with energies exceeding several nJ are hardly achievable with state of the art semiconductor based lasers and amplifiers, the FDML approach provides the potential for pulse energies reaching 100nJ at repetition rates of several 100kHz directly from the electrically pumped semiconductor based oscillator.

Fast wavelength swept lasers with tuning rates of 0.1-1MHz and sweep bandwidths of ~100nm in the near infrared are the light sources of choice for today's fastest optical coherence tomography (OCT) systems. OCT is a novel technique for high resolution biomedical imaging which finds widespread use from research setups to commercial systems already in clinical practice.[19-21]

In standard wavelength swept lasers, a narrowband optical filter is tuned over the gain spectrum of the laser medium. Lasing has to continuously build up from amplified spontaneous emission (ASE), causing a fundamental limit to the achievable sweep speed[22]. This limit can successfully be overcome using Fourier domain mode locked (FDML) lasers[17,18], allowing for a more than ~100 higher sweep speed and therefore ultrahigh OCT imaging speeds[23]. A main element of FDML lasers is the fibre delay line of ~1km in the laser cavity enabling the synchronization of the filter sweep frequency and the roundtrip time of light in the cavity. This concept is similar to the one presented by Telle and Tang[24]. The ideal FDML laser is a semiconductor based swept laser in a stationary operation mode, emitting periodic continuous-wave (cw) wavelength sweeps equivalent to highly chirped laser pulses. In this work we report for the first time on the optical compression of these sweeps, which is accomplished using a 15km long highly dispersive optical fibre. In this way, we introduce a new approach of ultrashort pulse generation with a very unique set of performance parameters, regarding repetition rate and output pulse energy. The combination of low repetition rate, high pulse energy and high plug wall efficiency might open the access to many new applications.

Standard mode locked semiconductor based lasers suffer from comparably low pulse energies due to the energy storage limit in the semiconductor gain medium. However, FDML ps or sub-ps pulses would have a unique advantage, since here the entire wavelength sweep with energies of up to 1µJ is optically stored within the long delay fibre in the laser cavity and not as polulation inversion in the gain medium. Similar to eXtreme chirped pulse amplification (X-CPA) concepts[9], FDML lasers therefore have the potential to overcome this limit. Apart from high pulse energies, another advantage is that FDML lasers in principle enable direct access to the phase, i.e. the chirp of the sweeps/pulses via control of the tunable bandpass filter and direct access to the amplitude by the current of the semiconductor gain medium. This means an FDML laser has a pulse shaper inherently built in. It should be emphasized that this method of ultrashort pulse generation is fundamentally different from conventional mode locking, such as the well known soliton mode locking and stretched-pulse (dispersion-managed) solutions to the Haus Master equation[25] as well as the recently discovered all-normal-dispersion[26], similariton[27] and soliton-similariton[28] regimes. Besides the fact that this concept might be an attractive candidate for future high energy, low repetition rate semiconductor pulse lasers, our findings, i.e. the measured compression factor, also provide valuable insight into the coherence of the FDML output.

In this work we demonstrate that pulse duration very critically depends on the coherence properties of the FDML laser, currently allowing for temporal compression down to 60-70ps. The experimental results are compared to numerical simulations based on a theoretical model of the FDML laser[29]. Simulations also enable us to give an outlook how pulse duration might significantly be improved in the future.

Results

Temporal compression of the FDML sweeps

The FDML resonator in Figure 1a uses a 1550±50nm semiconductor optical amplifier (SOA) as gain medium and a bulk Fabry-Pérot tuneable filter (BFP-TF)[23] with a finesse of ~400 for very high sweep speeds of v_{sweep}~250nm/µs at 2x390kHz repetition rate. The 524m fibre delay line is dispersion compensated to improve the coherence of the laser[30,31]. Light from the FDML output passes a second, single polarization (16dB polarization dependence) booster SOA which ensures a stable polarization state and acts as optical switch, only transmitting and amplifying a part of each forward (short to long wavelengths) sweep. This determines the temporal width of the sweep τ_{sweep}, the sweep bandwidth $\Delta\lambda_{sweep}$ and the centre wavelength λ_c of the sweep used for temporal compression. Our optical compressor is a 15km long dispersion compensation fibre (DCF), which is passed either once ("1x pass") or four times ("4x pass"). To ensure optimum compression, the filter drive parameters have to be chosen very accurately (see Methods). An additional chirp, which might be introduced by the rather slow ~18ns switching of the SOA gain, should be very small and can, if necessary, be compensated by fine tuning of the filter drive parameters (see Methods). For all measurements, a good polarization contrast is observed after the optical compressor. Figure 1b shows the wavelength tuning of the bandpass filter for 1x pass of the DCF (amplified part red). The pulses are analyzed with (i) a fast sampling oscilloscope and (ii) a 2nd harmonic intensity autocorrelator.

Internal FDML parameters and their impact on pulse duration

Figure 2a shows the ~127ps±3ps apparatus function of the sampling oscilloscope and photo diode, measured with pulses from a titanium sapphire laser (see Methods). Figure 2a also shows the signal from the shortest pulse (FWHM ~144ps±3ps). By numerical deconvolution a duration of ~68ps±12ps (assuming a Gaussian shape) can be estimated. The uncertainty of the pulse duration caused by electronic measurement and deconvolution was calculated from the fluctuations of the pulse duration on the sampling oscilloscope via error propagation methods (here: ±12ps). In this measurement, light passed the DCF once and the bandwidth $\Delta\lambda_{sweep}$ is set to ~6nm (τ_{sweep}~24ns) to reduce effects of higher order dispersion in the DCF. Figure 2b and 2c show the pulse durations for frequency detunings ranging from -1 to 1 Hz. It is obvious that already a slight detuning of the FDML filter drive frequency on the order of Δf~0.1 Hz (i.e. a relative frequency change of ~$3\cdot10^{-7}$) results in considerable temporal broadening of the pulses (increase of pulse duration by a factor of ~1.5). These values of detuning are far too small to significantly change the amount of dispersion required for compression. This shows that internal laser dynamics governs the output of the FDML sweep rather than only specifications of the individual components, e.g. especially the sweep filter. As shown in Figure 2c and 2d, the experimental values found with our setup are in good agreement with numerical simulations using the theoretical model described in [29,32], even though the discrepancy between theory and experiment reaches a factor of up to ~2. The deviation of the minimum value of the achievable pulse duration measured in the experiment to the minimum value predicted by theory is ~30%. However, the observed asymmetry for detuning is much less pronounced in the theory, only the trend is predicted qualitatively. To mimic experimental conditions (sampling oscilloscope) and suppress fluctuations, the theoretical pulse durations have been achieved by averaging the simulated intensity profiles of over 20 non-sequential pulses, evaluating every 100th roundtrip. In this way, a variation of the pulse duration of up to ~20% is observed depending on the chosen trigger condition for averaging, giving an idea of the uncertainty of the presented theoretical data.

For a more systematic investigation, Figure 2d shows the minimum achievable pulse duration τ_{pulse} in case of different spectral widths $\Delta\lambda_{Filter}$ of the BFP-TF for 1x pass ($\Delta\lambda_{sweep}$~6nm, τ_{sweep}~24ns, v_{sweep}~250nm/µs) and 4x pass ($\Delta\lambda_{sweep}$~1.5nm, τ_{sweep}~24ns, v_{sweep}~62.5nm/µs) of the DCF fibre compressor. With a fixed finesse of ~400 (mainly given by the coatings) the filter width $\Delta\lambda_{Filter}$ can be adjusted by adapting the free spectral range (FSR) of the BFP-TF. Depending on $\Delta\lambda_{Filter}$, the FSR therefore ranges from ~40nm to ~170nm. The measurements indicate that τ_{pulse} correlates to a certain extent with $\Delta\lambda_{Filter}$ (smaller $\Delta\lambda_{Filter}$ yields smaller τ_{pulse}), but also with v_{sweep} (larger v_{sweep} gives shorter τ_{pulse} for same $\Delta\lambda_{Filter}$). Currently, there are two different limits to the filter width $\Delta\lambda_{Filter}$ accessible in the experiment: 1) For the case of 1x pass of the DCF fibre compressor, $\Delta\lambda_{Filter}$ was not reduced below ~315pm since the necessary further reduction of the FSR requires an increase in mechanical excursion of the BFP-TF which is not possible due to mechanical restrictions. 2) For the case of 4x pass of the DCF fibre compressor, mechanical restrictions are currently not limiting. The 4x pass generates 4x more dispersion, so it can compensate a sweep/pulse with 4x more chirp. 4x higher chirp of the sweep translates to a 4x slower sweep speed of the FDML laser, reducing the mechanical requirements for the filter. So in the case of 4x pass we were not able to reduce $\Delta\lambda_{Filter}$ below ~110pm because the center wavelength λ_c of the sweep does not coincide with the gain maximum and, therefore, smaller values of FSR induce lasing at wrong wavelengths. In the future, the application of a BFP-TF with higher finesse can enable considerably smaller filter widths $\Delta\lambda_{Filter}$. Currently, a minimum pulse duration τ_{pulse} of ~68ps±12ps has been achieved in both cases, 1x pass and 4x pass.

Intensity autocorrelation and continuum generation

In order to confirm the electronic measurements with autocorrelation data, we applied erbium doped fibre amplification (EDFA) to raise the power levels (1x pass of DCF). To minimize non-linear effects and prevent pulse breakup, we limited our EDFA gain to ~16dB, resulting in a pulse width τ_{pulse}~59ps±12ps, measured with the sampling oscilloscope. Figure 3a shows the corresponding autocorrelation signal, which exhibits two features. A narrow coherence spike (consistent with the bandwidth limit of ~600fs) is centered on top of a broad pedestal (FWHM, autocorrelation time τ_{AC}~89ps) (contrast ratio ~1:1). This implies a pulse width of τ_{pulse}~63ps consistent with the results acquired with the sampling oscilloscope, but also indicates the existence of an intensity substructure[33,34], caused by internal FDML dynamics (see Discussion)[33,34]. Note that the uncertainty of the autocorrelation measurement itself can be considered negligible. However, the error caused by the unknown pulse shape can be estimated to be ~10ps (Gaussian: 63ps; $Sinc^2$: 67ps; $Sech^2$: 58ps). The average power and the instantaneous power after the DCF are ~2.2mW and ~96W, respectively. This corresponds to a pulse energy of ~5.6nJ at a pulse repetition rate of 390kHz. Figure 3b (top) shows the spectrum after the booster SOA, whereas Figure 3b (bottom) demonstrates the potential of continuum generation, realized by propagation of the pulses (pulse energy ~11nJ) through 1.7km of dispersion shifted fibre (DSF). We observe remarkable spectral flatness over ~100nm even on a linear scale. Even though continuum can be generated even with cw-sources, the extremely low average power of our source might be attractive in several configurations.

Discussion

From a laser physics point of view, the observed pulse duration τ_{pulse} gives a direct indication of the degree of coherence in the FDML sweep. In case of a fully incoherent wavelength sweep, the shortest achievable pulse length τ_{inc} for the compression is determined by the instantaneous linewidth $\Delta\lambda_{inst}$ [32,35] and the sweep speed v_{sweep} (see Methods), as sketched in Figure 4a (dark green curve: 1x pass, dark blue curve: 4x pass). Temporal compression of a per se incoherent wavelength swept ASE[36,37] with adjustable instantaneous linewidth[36] (see Methods) demonstrates very good agreement with this model (see crosses in Figure 4a). Assuming equal filter width, the minimum pulse lengths achieved with incoherent light are ~20x longer than with FDML (compare achievable pulse durations for incoherent wavelength swept ASE (Figure 4a) and for FDML operation (Figure 2b)). In case of a fully coherent wavelength sweep with $\Delta\lambda_{sweep}$~6nm (1x pass) or $\Delta\lambda_{sweep}$~1.5nm (4x pass), the minimum achievable pulse durations τ_{coh} are ~600fs or ~2.4ps (see Methods), both are considerably smaller than the ~68ps achieved with FDML. This indicates that the FDML sweep has non-coherent contributions in its amplitude and phase evolution. However, a purely incoherent sweep can never generate a τ_{pulse} of ~68ps, as illustrated in Figure 4b (only 4x pass), since all values of the dark blue curve (expected pulse duration for incoherent sweep, see Methods) are at least ~5x larger. Based on the measured instantaneous linewidth[31,35] (not filter width!) of ~10pm (see Methods), the red oval indicates the approximate operation range of the FDML laser, clearly located within the parameter range of partial coherence (yellow area).

Hence the entire FDML sweep is at least partially or section wise coherent. The question whether the electric field of the FDML sweep consists of many sections with internally high phase and amplitude stability but random phases between each other, or if random phase and amplitude fluctuations have some increased probability near the optimum phase and amplitude evolution cannot be judged at this point with certainty. However, since we operate our FDML laser in the ultra-stable regime as observed by Kraetschmer et al.[38], it can be speculated that the FDML sweeps show a section-wise very good coherence, interrupted by wavelength/phase discontinuities. This assumption is supported by the observation of interference fringe signals from a Mach-Zehnder interferometer, where sections of very smooth and clean fringe signals can be observed, separated by more unstable regions of phase discontinuities. After compression, the weakly defined phase between the different sections causes strong amplitude fluctuations, which have also been observed in the numerical simulations.

To conclude, in this work we demonstrate for the first time the temporal compression of the wavelength swept cw output of an FDML laser. ~60-70ps pulses at a repetition rate of 390kHz have been achieved. Because of uncompensated higher order chirp, only 6nm sweep range has been used, which currently is the reason for limited pulse energies of ~140pJ (without EDFA) and ~5.6nJ (with EDFA). Concerning the achievable pulse energy, these results cannot compete with master oscillator fiber power amplifier (MOFA) systems[39], but are comparable to semiconductor based, optically pumped VCSELs[15,16] or semiconductor based MOPA systems[12,14]. Nevertheless, it should be emphasized that in spite of current experimental restrictions, already the ~140pJ is higher than typical pulse energies achievable with conventionally mode locked SOA based semiconductor lasers[9], even in the case of using an eXtreme chirped pulse oscillator approach[40]. In the future, the additional application of chirped fibre Bragg gratings[30] for arbitrary dispersion compensation might make >100nm sweep ranges usable, which would already push the pulse energy of the ~60-70ps long pulses directly from this laser oscillator without amplification well into the nJ range, even including compressor losses[30]. Moreover, the additional use of chirped fibre Bragg gratings could minimize non-linear effects in the optical compressor and therefore reduce or prevent the effect of pulse break-up limiting pulse energy. For example if the final compression from nanoseconds to picoseconds is performed by a chirped fibre Bragg grating at the very end of the fibre setup, the propagation length of the pulse at maximum peak power can be minimized. Alternatively a final bulk optics compressor may be used.

Using an EDFA, a pulse energy of more than 11nJ is measured, sufficient for the generation of a spectrally flat continuum. The ~60-70ps pulse duration is far shorter than the result expected from purely incoherent superposition, indicating at least partially coherent superposition of the different spectral components of the FDML sweep during the compression process. The experiments are in good agreement with numerical simulations, which predict that <10ps pulses can be achieved with the current setup by simply using a more narrowband sweep filter (higher finesse). Remarkably, an even further reduction in pulse duration is predicted by theory reaching almost bandwidth limited pulses if, in addition to a more narrowband filter, the cavity dispersion is further reduced. These findings indicate that, in the future, modifications in the experiment will enable the generation of considerably shorter pulses well into the lower picosecond range.

However, it should be emphasized that even the 60-70ps pulse durations of our setup presented here are highly attractive for many applications. Usually ps pulses have a very narrow spectrum due to the time bandwidth product, this makes them prone to parasitic coherent non-linear effects like Brillouin scattering[41] which limits the maximum achievable pulse energy, especially in fibre based delivery systems. Also all applications which are susceptible to interference caused by spurious reflections greatly benefit from the wide spectral bandwidth. In imaging applications the wide spectrum reduces problems with speckle noise, in sensing applications it reduces spectral modulations caused by backreflections.

Considering the described potential for improvement, FDML lasers might become an interesting option as compact, all fibre based and highly robust source for ultrashort pulses. Even though pulse energies from the FDML laser without EDFA currently do not reach the performance of state of the art semiconductor based pulse laser systems[9,15,16], the low repetition rate of FDML lasers, the fact that they are constructed of all fibre based low cost telecom components and the fact that they are electrically pumped may make them highly attractive for applications that demand compactness, low power consumption and robust design.

Methods

FDML laser resonator and booster SOA

The optical delay line in the FDML resonator consists of 246m standard single mode fibre (Corning SMF 28) and 16m dispersion compensation fibre (OFS-HFDK), used to minimize residual dispersion in the resonator in the wavelength range around 1560nm to less than 0.25ps/nm. A sigma-ring configuration is used with an optical circulator (CIR) and a Faraday rotation mirror (FRM), so light passes the delay line twice during one resonator roundtrip and birefringence effects in the delay line are cancelled. The circulator and the optical isolator (ISO) ensure unidirectional lasing. 50% of the optical power is coupled out via a fused fibre coupler (FC). The gain of the SOA in the cavity is polarization independent (Covega-SOA1117), whereas the gain of the booster SOA is polarization dependent (Covega-BOA1004). Polarization controllers (PC) enable adjustment of the polarization state in the fibre. A two channel, phase locked voltage control is used. Channel 1 (DC+AC voltage) generates a sinusoidal wavelength tuning of the BFP-TF. The DC-voltage is actively feed-back controlled to stabilize the centre wavelength λ_c using an optical spectrum analyzer (OSA). Channel 2 yields a synchronous switching of the gain of the booster SOA via a fast current modulator (Wieserlabs WL-LDC10D). Light is either amplified from ~10mW average power before the booster SOA to ~47mW instantaneous power (SOA on) after the booster SOA or suppressed by a factor >10dB (SOA off).

Temporal compression and filter drive parameters

The optical compressor is a ~15km long highly dispersive DCF fibre (OFS type HFDK). Light passes the fibre once ("1x pass") or 4 times ("4x pass"). For all experiments a centre wavelength of λ_c=1560nm is chosen since this is a good trade-off between large amount of negative dispersion (-4ns/nm) of the DCF, minimal loss (~-8.5dB) and good dispersion compensation in the FDML resonator. The ~211nm total filter sweep range of the BFP-TF is set such that the filter sweep speed $v_{sweep}(\lambda_c)$ equals the inverse of the magnitude of the dispersion in the DCF compressor. To guarantee minimal loss, a very high sweep speed of the BFP-TF is crucial, since it minimizes the required DCF fibre length. However, some measurements are performed with light passing the ~15km of DCF fibre four times (two directions and two orthogonal polarizations) using an optical circulator and a polarization beam splitter. In this case dispersion and loss are increased and the required total filter sweep range (~53nm) is reduced by a factor of 4. Due to the dispersion slope of the DCF and the sinusoidal drive of the optical filter, there exists a limit for temporal compression $\tau_{com}(\Delta\lambda_{Sweep})$ caused by remaining higher order dispersion, depending on the chosen bandwidth $\Delta\lambda_{Sweep}$. Besides accurate adjustment of the total filter sweep range, a reasonable choice of the phase difference $\Delta\Phi$ between filter drive and booster SOA modulation signal is important, so the curvature of the drive can partly compensate the dispersion slope in the DCF. Simulations using the measured dispersion[42] of the DCF predict τ_{com} <10ps for an optical sweep bandwidth $\Delta\lambda_{sweep}$~6nm (1x pass) and $\Delta\lambda_{sweep}$~1.5nm (4x pass).

Erbium doped fibre amplification

The erbium doped fibre amplifier (EDFA) used in this experiment consists of ~6m of doped fibre (MetroGain-M12-980-125) and two wavelength division multiplexers (WDM). Pump light from a pump diode (JDSU-S34) at 1457nm is used in forward direction. Benefiting from a small duty cycle (~1%), an amplification of the truncated sweep (τ_{sweep}~24ns, $\Delta\lambda$~6nm) by at least 22dB is easily possible. By far higher amplification factors can be achieved, but the spectral shape and the pulse duration degrade due to non-linear processes in the compression fibre. However, for our experiment the 22dB amplification is sufficient to measure a 2^{nd} harmonic intensity autocorrelation.

Pulse detection: Sampling oscilloscope and autocorrelator

For measurement and characterization of the pulse duration two methods are used: (i) A direct electronic measurement using a 8GHz photo receiver (Kyosemi Corporation-KPDX10GV3) and an analog sampling oscilloscope (Tectronix 7603). (ii) A home built 2^{nd} harmonic intensity autocorrelator. For the electronic measurement 1% of the compressed light is adjusted in power by a bulk optic variable attenuator. To guarantee proper triggering of the sampling oscilloscope (~25ps rise time), the train of pulses is split by a 50/50 fibre coupler, one part is directly used to trigger the oscilloscope (2GHz photodiode (Wieserlabs WL-PD2GA)), the other part is optically delayed by a length of ~100m single mode fibre and measured with the fast photodiode. In order to determine the apparatus function of photodiode and oscilloscope, short pulses (several ps) from the amplified output of a 74MHz titanium sapphire oscillator (Femtolasers Integral, 975nm part post-amplified by Yb fibre amplifier – setup described in [43]) were measured in the same manner yielding a FWHM of ~127ps±3ps. The home-built 2nd harmonic intensity autocorrelator for measurements up to 500ps pulse length uses a BIBO crystal in a noncollinear geometry for frequency doubling generating a background free signal. The frequency doubled signal is detected with an integrating silicon photodiode (Wieserlabs WL IPD4A) adjusted to 250µs integration time and a read out rate of ~900Hz. Each data point is a 100 times average.

Theoretical model: Minimum pulse duration after compression

In order to gain a comprehensive understanding of pulse generation based on temporal compression of wavelength-swept waveforms, it is important to theoretically analyze the minimum achievable pulse duration for both limiting cases, assuming fully coherent and fully incoherent sweeps. This is the aim of the following description.

For a fully coherent sweep, which is 100% identical to a highly chirped laser pulse, the minimum achievable pulse duration τ_{coh} is given by the total sweep bandwidth and the time-bandwidth product (0.44 for a Gaussian envelope).

$$\tau_{coh} = 0.44 \cdot \frac{\lambda_c^2}{\Delta\lambda_{sweep} \cdot c}$$

To estimate the shortest pulse duration that can be achieved by compressing a fully incoherent wavelength swept waveform, we assume a tuneable optical bandpass filter with a spectral width $\Delta\lambda_{Filter}$ where the filter passband is swept over a spectral range $\Delta\lambda_{sweep}$ in a time τ_{sweep}. The tuning speed is assumed to be constant:

$$v_{sweep} = \frac{d\lambda}{dt} = \frac{\Delta\lambda_{sweep}}{\tau_{sweep}} = const.$$

Here, the ratio between filter bandwidth $\Delta\lambda_{Filter}$ and tuning range $\Delta\lambda_{sweep}$ defines the number of resolvable wavelengths $n = \Delta\lambda_{sweep}/\Delta\lambda_{Filter}$ within the sweep. Note that, in the case of tunable lasers with mode competition, the output can exhibit a more narrowband instantaneous linewidth $\Delta\lambda_{inst}$ than the width of the filter $\Delta\lambda_{Filter}$. Therefore, generally the number of resolvable wavelengths has to be defined as $n = \Delta\lambda_{sweep}/\Delta\lambda_{inst}$. The minimum pulse duration achievable by compressing fully incoherent wavelength sweeps is determined by two different limits (limit 1 and limit 2) which are discussed separately in the following. Depending on the sweep speed and the spectral filter width either limit 1 or limit 2 is the dominant contribution.

Limit 1, which arises as a direct consequence of wavelength sweeping, is the dominant contribution in the case of a sufficiently slow sweeping operation or a sufficiently wide filter. In this case, the resolvable spectral sections in the wavelength swept waveform are equivalent to resolvable temporal sections. Consequently, we can define a switching time of $\tau_{switch} = \tau_{sweep}/n$, where τ_{switch} is the time the filter needs to sweep over its bandwidth. Since amplitude and phase of the optical waveform fluctuate randomly during each time interval τ_{switch}, this, under given assumptions, is the shortest pulse duration which can be expected by compressing a wavelength sweep generated from an incoherent light source. So the minimum achievable incoherent pulse width $\tau_{inc} = \tau_{switch}$ is determined by the filter width (or the instantaneous linewidth) and the sweep speed:

$$\tau_{inc} = \frac{\Delta\lambda_{inst}}{v_{sweep}} \quad \text{(incoherent, slow)}$$

More narrowband filters and higher sweep speed will result in shorter pulses.

However, there is an additional condition determining the minimum pulse duration. The time-bandwidth limit (limit 2) sets a lower boundary to the shortest pulse duration, and in incoherent swept sources the filterwidth $\Delta\lambda_{Filter}$ or the instantaneous linewidth $\Delta\lambda_{inst}$ determines this limit (in fully coherent sources it is the sweep width $\Delta\lambda_{sweep}$). Limit 2 is the dominant contribution assuming a sufficiently high tuning speed (or sufficiently narrowband filter widths). In this case, we can estimate the minimum achievable pulse duration for a Gaussian shape at a centre wavelength of λ_c and the speed of light c:

$$\tau_{inc} = 0.44 \cdot \frac{\lambda_c^2}{\lambda_{inst} \cdot c} = n \cdot \tau_{coh} \text{ (incoherent, fast)}$$

In general, the minimum achievable pulse duration τ_{inc} of fully incoherent swept sources can be obtained by convoluting both contributions (limit 1 and limit 2). Assuming Gaussian shaped temporal windows (τ_{inc} is FWHM) the minimum pulse duration reads:

$$\tau_{inc} = \sqrt{\left(0.44 \cdot \frac{\lambda_c^2}{\lambda_{inst} \cdot c}\right)^2 + \left(\frac{\Delta\lambda_{\text{inst}}}{v_{sweep}}\right)^2} \text{ (incoherent)}$$

Experimentally, fully incoherent swept sources can be realized by filtering temporally incoherent light, like a thermal source, or, in our case, spontaneous emission from an SOA. Such a source has been described in[36,37]. In such sources, the instantaneous linewidth $\Delta\lambda_{inst}$ is always identical to the filter width.

Measurement of the instantaneous linewidth of the FDML laser

Measuring the instantaneous linewidth $\Delta\lambda_{inst}$ of a rapidly wavelength swept light source is not trivial, especially since, at very high sweep speed, the values approach the time bandwidth product.[35] One approach, that is very common in swept source OCT, but yielding only an average value for the instantaneous spectrum (average over one sweep), is the following: The interference signal from a Michelson interferometer is acquired and a combined analysis of phase jitter and loss in fringe contrast using a Fourier transform is used to determine the coherence length and with it the instantaneous spectrum. Because the fringe frequency increases beyond our measurement bandwidth (1 GHz – Tektronix real time oscilloscope type DPO 7104), for a very narrow instantaneous linewidth $\Delta\lambda_{inst}$, we cannot measure down to the -6dB coherence roll-off, but only to ~-0.5dB. Extrapolation of our data allows for a rough estimation of $\Delta\lambda_{inst}$ to ~10pm, which corresponds to ~1.2GHz at 1560nm. This value is used in the diagram in Figure 4b to estimate the level of coherence in the FDML sweep.

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Author contributions

C.M.E. performed the measurements. C.M.E, W.W., B.B. and T.K. implemented the experiments. C.M.E. and R.H. had the idea and designed the experiments. S.T. and C.J. coded the software and ran the simulations. S.T. and C.J. analyzed and interpreted the simulation results. C.M.E. and R.H. interpreted the experimental results. C.J. supervised the theoretical work and R.H. supervised the experimental work.

Competing Financial Interest Statements

The authors declare no competing financial interests.

Figure Captions

Figure 1. Experimental setup and bandpass filter control

a. FDML resonator operated at 1560nm and 390kHz repetition rate, post-amplification devices, dispersion compensation fibre (DCF) used for temporal compression and the detection system for the short pulses. (SOA: Semiconductor optical amplifier, ISO: Optical isolator, PC: Polarization controller, FRM: Faraday rotation mirror, CIR: Optical circulator, FC: Fused fibre coupler, BFP-TF: Bulk Fabry-Pérot tuneable filter, EDFA: Erbium doped fibre amplifier). b. Typical wavelength tuning (1x pass of DCF) of the optical bandpass filter (black), including the part used for temporal compression (red).

Figure 2. Pulses from FDML laser

a. Apparatus function of photodiode and oscilloscope and the pulse generated from the compressed FDML sweep (1x pass of DCF and bandwidth $\Delta\lambda_{sweep}$~6nm). Deconvolution yields τ_{pulse}~68ps. b. Pulses from the FDML laser for different FDML frequency detunings. All illustrations showing pulses are based on digitized photographs of the analog sampling oscilloscope. c. Degradation of pulse width (FWHM) for FDML frequency detuning (~$3*10^{-7}$ relative to drive frequency) showing measured values and results from theory. d. Pulse width (FWHM) plotted against spectral width (FWHM) of the tunable bandpass filter showing measured values in case of a 4x pass and 1x pass of the DCF fibre and results from theory in case of 1x pass of the DCF fibre.

Figure 3. Autocorrelation signal and continuum generation

a. Background free 2nd harmonic intensity autocorrelation signal of the amplified FDML pulse (1x pass of DCF, $\Delta\lambda_{sweep}$~6nm). A narrow coherence spike (time-bandwidth product of ~600fs) is centred on top of a broad pedestal (τ_{AC}~89ps) implying a pulse width (FWHM) τ_{pulse}~63ps. b. Time averaged spectrum after the booster SOA (top) and very flat continuum (linear scale!) measured after ~15km

DCF and additional 1.7km dispersion shifted fibre (DSF) (bottom). (Small satellite peaks result from adjacent Fabry-Pérot modes, remaining after suppression by the booster SOA).

Figure 4. Pulse duration for incoherent sweeps: Experiment and theory

a. Pulse duration of the temporally compressed output of a wavelength swept light source as function of the instantaneous linewidth $\Delta\lambda_{inst}$, assuming purely incoherent superposition (dark blue curve: 4x pass, dark green curve : 1x pass), each case defined by the convolution of two contributions: (i) time-bandwidth product of $\Delta\lambda_{inst}$ (black dashed curve) and (ii) limitation due to sweep speed of the optical bandpass filter (blue dashed curve: 4x pass, green dashed curve: 1x pass). The crosses show the experimental results with an incoherent wavelength swept ASE source for 4x pass of DCF and different bandwidths $\Delta\lambda_{sweep}$. b. Zoomed view, representing current FDML performance for 4x pass of DCF (red oval), clearly lying within the partially coherent region (yellow area).

Figures

Figure 1:

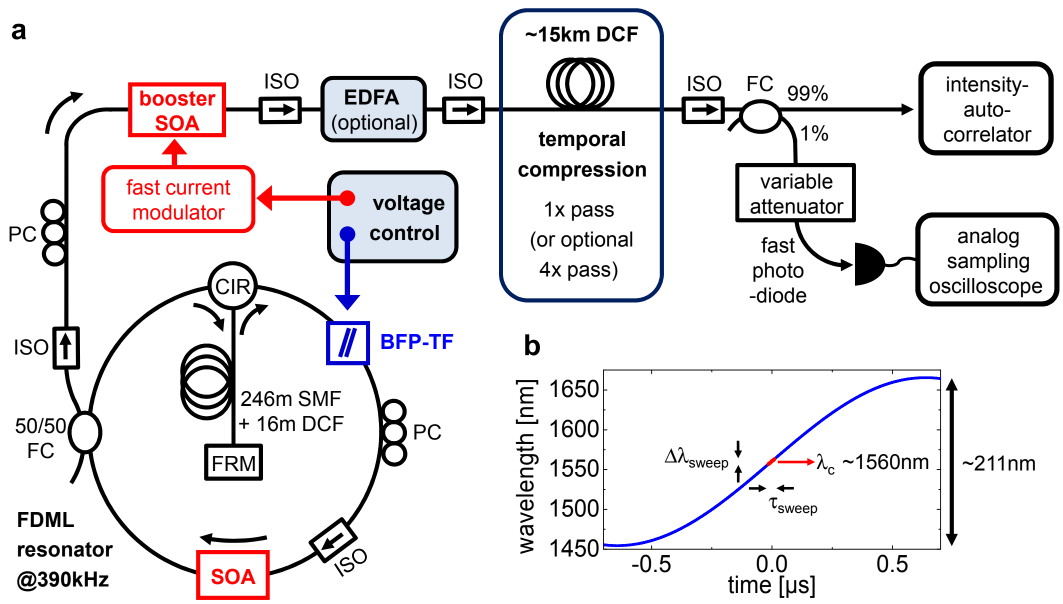


Figure 2:

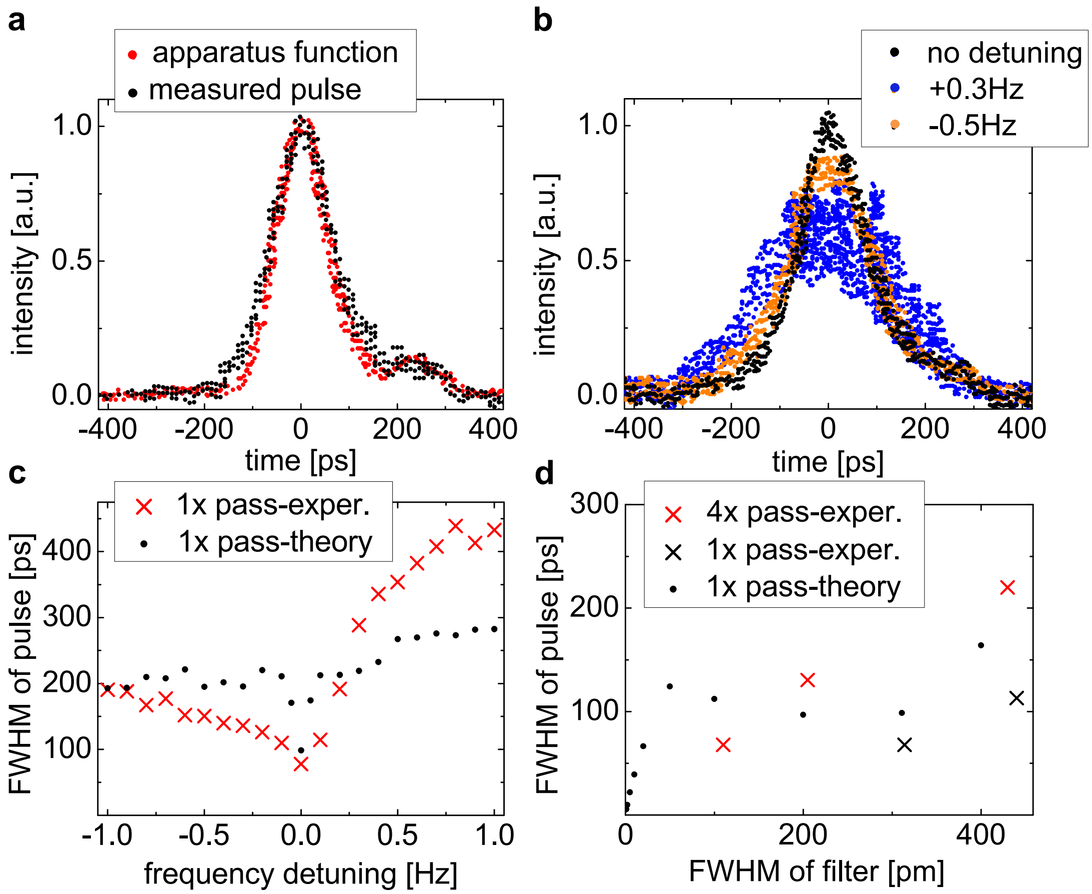

a
apparatus function
measured pulse
1.0
0.5
0.0
intensity [a.u.]
-400
-200
0
200
400
time [ps]
b
no detuning
+0.3Hz
-0.5Hz
1.0
0.5
0.0
intensity [a.u.]
-400
-200
0
200
400
time [ps]
c
1x pass-exper.
1x pass-theory
400
300
200
100
FWHM of pulse [ps]
-1.0
-0.5
0.0
0.5
1.0
frequency detuning [Hz]
d
4x pass-exper.
1x pass-exper.
1x pass-theory
300
200
100
FWHM of pulse [ps]
0
200
400
FWHM of filter [pm]

Figure 3:

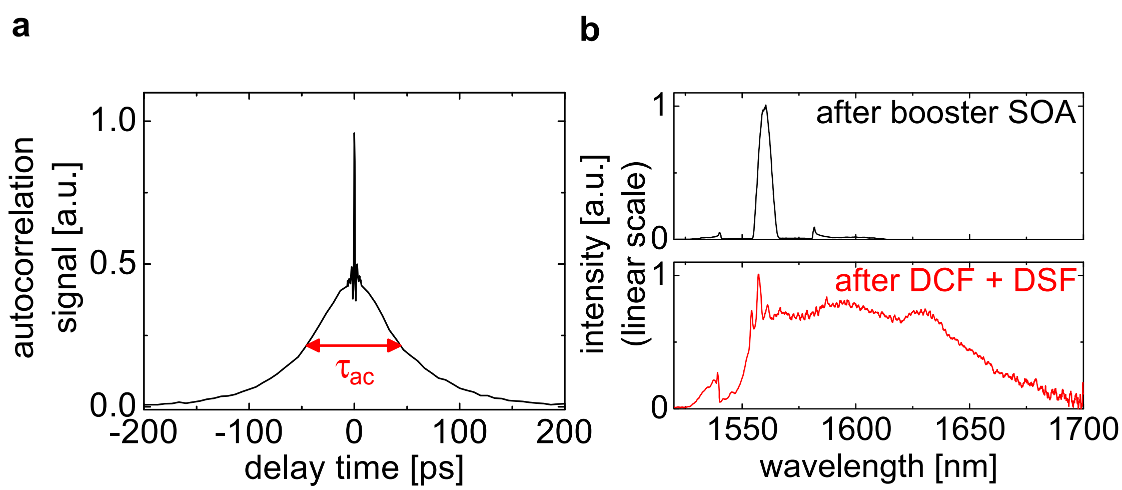
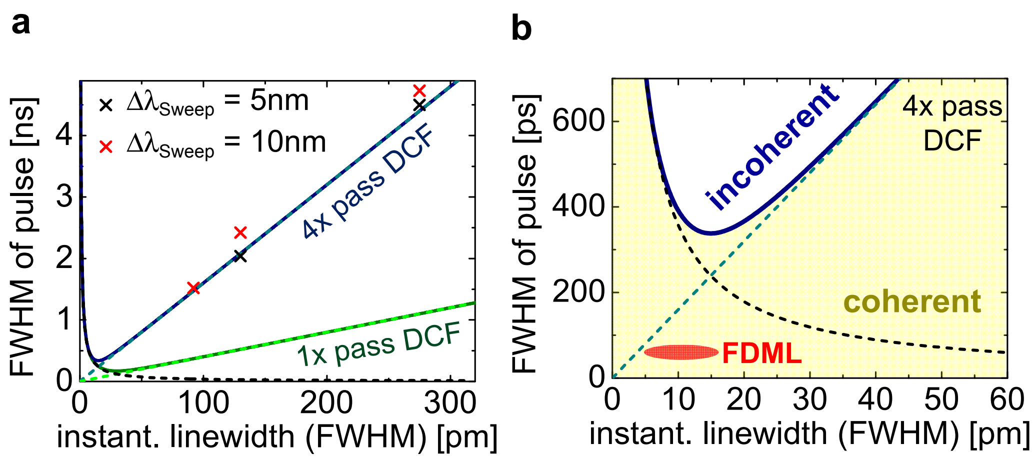

a
b
autocorrelation signal [a.u.]
1.0
0.5
0.0
τ_{ac}
-200
-100
0
100
200
delay time [ps]
intensity [a.u.] (linear scale)
after booster SOA
after DCF + DSF
1
0
1
0
1550
1600
1650
1700
wavelength [nm]

Figure 4:


a
b
× Δλ_Sweep = 5nm
× Δλ_Sweep = 10nm
4x pass DCF
1x pass DCF
FWHM of pulse [ns]
0
1
2
3
4
0
100
200
300
instant. linewidth (FWHM) [pm]
incoherent
4x pass
DCF
coherent
FDML
FWHM of pulse [ps]
0
200
400
600
0
10
20
30
40
50
60
instant. linewidth (FWHM) [pm]