Characterization of ultrashort optical pulse properties by amplitude-modulation-balanced heterodyne gating

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We present a general approach for the measurement of the properties of optical pulses by exploiting features of the optical carrier domain. We demonstrate the principle of a novel balanced detection scheme that avoids the difficulties associated with homodyne detection in the baseband used in linear optical sampling methods so far. The residual timing instability of the repetition rate synchronization between mode-locked lasers is measured with the new detection technique. © 2005 Optical Society of America

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The measurement of light pulse properties such as temporal shape or timing jitter is of broad interest, as, for example, for the characterization of mode-locked lasers and of their synchronization or for monitoring high-bit-rate telecommunication signals by optical sampling. Such measurements of pulse properties are usually based on intensity cross correlation between the signal pulses and the short synchronized gating pulses, employing a nonlinear optical effect such as, for example, sum-frequency generation (SFG) in crystals[1] or cross-phase modulation in fibers.[2] This nonlinear approach, however, suffers from poor conversion efficiency of the nonlinear process, and more-sensitive methods are required if only low light power is available. In such a case, the field instead of the intensity cross correlation can be used.[3] This linear approach is applicable in the entire region of overlapping spectra of the signal and gating pulses and requires that the gating pulses are time–bandwidth limited. Figure 1 shows an exemplary comparison between the shape of the laser pulses of a mode-locked Er:Yb:glass laser[4] simultaneously measured by nonlinear sampling using SFG in a type II phase-matched β-barium borate crystal and heterodyne linear optical sampling that will be introduced in this Letter. The slight difference between the detected pulse shapes can be ascribed to a deviation from the required time–bandwidth limit of the sampling laser in the linear case. Balanced homodyne detection measuring quadratures of the optical field were presented earlier.[5,6] Dorrer *et al.*[7] applied linear sampling using balanced homodyne detection of two orthogonal field quadratures to the characterization of telecommunication signals. However, the homodyne approach is based on detection in the baseband and is thus inherently sensitive to technical disturbances such as acoustics, noisy optical background signals, or temperature drifts of the setup. Jiang *et al.*[8] have shown that such problems can partially be avoided using an interferometric modulation scheme, which, however, has limited bandwidth and is only implemented for signals from the same source.

In this Letter, however, we demonstrate the first implementation, to our knowledge, of a field cross-correlation heterodyne gating technique for signals from independent sources avoiding the difficulties associated with baseband detection for frequencies up to the 10 MHz range. We introduce a stabilized frequency offset between the optical carriers and detect the amplitude of the resulting beat note. To obtain a beat signal, the sampling laser must be synchronized with the signal pulses.[9] This determines the repetition rate of the mode-locked sampling laser and thus the line spacing of its frequency comb. For a phase-insensitive measurement of the beat-note amplitude, the comb is additionally locked to the optical carrier of the signal, which we implement by an improved feed-forward scheme using an external acousto-optic modulator (AOM).[10]

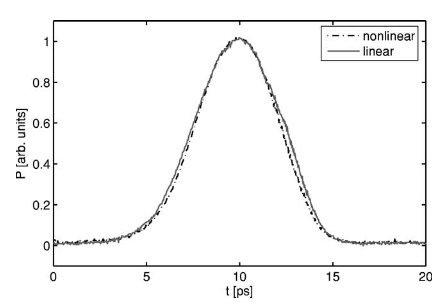

Fig. 1. Comparison between pulse shapes simultaneously measured by nonlinear and linear optical sampling.

The experimental setup is schematically shown in Fig. 2. We use a 10 GHz pulse train from a mode-locked Er:Yb:glass laser as a model signal (laser 1 in Fig. 2, $\tau_{\mathrm{FWHM}} \approx 5.4$ ps, $\lambda = 1538$ nm). As a sampling pulse source, an erbium-doped fiber laser with a pulse length below 70 fs and a repetition rate of $f_{rep} \approx 56.3$ MHz is employed (laser 2). It comprises a free-space section for control of the repetition rate with a piezo-mounted mirror.[11] For the pulse envelope synchronization, the 9.862 GHz signal rate and the 175th harmonic of the sampling rate near 9.862 GHz are detected by fast InGaAs photodiodes PD1 and PD2 and used to phase lock the sampling rate to the signal rate. Hence, only every 175th signal pulse is sampled.

The signal beam coming from laser 1 is indicated by the gray lines in Fig. 2. The p-polarized component traverses polarizing beam splitter PBS1 and a variable delay D1. It is overlapped in beam splitter BS1 with the p-polarized component coming from the sampling laser (indicated as a dark line in Fig. 2). The resulting beat signal is detected with photodiode PD3 with the maximum temporal overlap adjusted by D1. Since the repetition rates of the lasers are synchronized, the frequency fluctuations of the detected beat mainly correspond to the fluctuations of the difference between their carrier-envelope offset (ceo) frequencies.[12] The frequency fluctuations are fed forward to an AOM in a second path, thus stabilizing the optical carriers with respect to each other.

As indicated by the dashed lines in Fig. 2, the beat signal detected by PD3 is filtered and mixed with an electrical local oscillator (LO) signal in the 10 MHz range. The sum frequency is divided by a factor of 2 and the resulting signal with frequency $\nu_{\mathrm{AOM}} = (\nu_{\mathrm{PD3}} + \nu_{\mathrm{LO}})/2$ is fed forward to the AOM. The AOM driving frequency thus fluctuates exactly half as much as the optical frequency, which is to be corrected by a double pass through the AOM, and the stabilized beat frequency is given by ν_{LO}. As a refinement of the original feed-forward scheme,[10] the double pass is introduced and retroreflector RR is used for reflection of the first-order diffracted beam to avoid a conversion of driving frequency fluctuations to power fluctuations due to beam-pointing effects of the AOM. After the double pass, the polarization is changed by 90° due to the $\lambda/4$-wave plate, and the feed-forward stabilized, p-polarized beam is transmitted through PBS1.

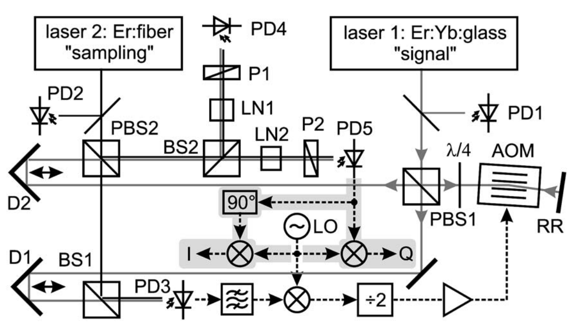

Fig. 2. Experimental setup. The gray shaded part was not implemented in this work but is discussed in the last paragraph. See text for further details.

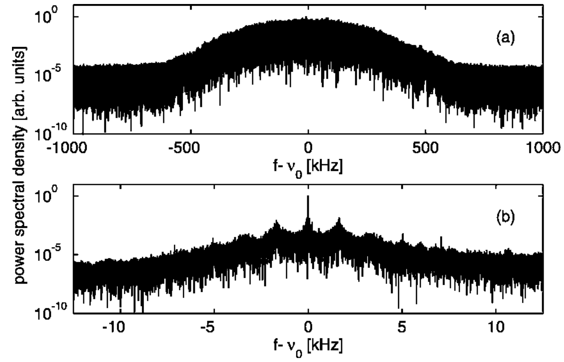

Fig. 3. Carrier beat spectra between repetition-rate-synchronized lasers 1 and 2 (a) before and (b) after feed-forward stabilization. Please notice the different frequency scales.

After passing variable delay D2, the beam is spatially overlapped in PBS2 with the s-polarized beam coming from the sampling laser. For linear optical sampling only, it is sufficient to detect the amplitude of the beat note with a photodiode after mixing the two orthogonally polarized beams in a polarizer. Sweeping over the pulse shape of laser 1 is accomplished by scanning delay D2. In this configuration, a simple way to determine the residual timing instability of the repetition rate synchronization is to use the setup as a slope detector, preferably in an amplitude-modulation- (AM-) compensated scheme. Such a double slope detection is implemented in our setup by the symmetric arrangement around 50:50 beam splitter BS2: In both arms, the orthogonally polarized signal and sampling beams experience a relative delay due to the group birefringence of $\Delta n = -0.086$ of the 1 cm long $LiNbO_3$ crystals LN1 and LN2. They are oriented so as to generate relative group delays of the beams with opposite signs, resulting in an overall relative delay of ≈ 5.7 ps. Therefore, the difference of the photocurrents detected by PD4 and PD5 reflects the timing fluctuations while being relatively insensitive to intensity fluctuations. The power of the photodiode signals, i.e., the instantaneous modulus square of the heterodyne signal at the LO frequency, is measured by two narrowband powermeters and recorded with a two-channel digitizing oscilloscope. The instantaneous timing error is calculated from the difference ΔV of these power readings.

To demonstrate the effect of the feed-forward stabilization, we compare the beat spectra observed before and after the feed-forward stabilization. To obtain the spectra, we adjusted delays D1 and D2 for maximum beat signals on photodiodes PD3 and PD4 and recorded their temporal evolution using an electric sampling oscilloscope. The spectra were obtained by fast Fourier transform (FFT) of the recorded signals. Without stabilization [Fig. 3(a)], the beat frequency strongly fluctuates within an ≈ 800 kHz broad frequency band, caused by the fluctuations of the difference between the ceo frequencies of the two lasers. After stabilization [Fig. 3(b)], a sharp, stationary peak is observed on an only ≈ 10 kHz broad pedestal. The width of the peak is limited by the spectral resolution of the FFT spectrum analysis method. The residual pedestal is due to time delay in the feed-forward scheme. The shape of the pedestal depends on the bandwidth of the phase-locked loop (PLL) for the repetition rate synchronization and the side-bands are identified as servo bumps. This can be explained by slight tilting errors of the piezo-mounted mirror in the sampling laser, causing a modulation of losses in the cavity, which in turn leads to a modulation of the ceo frequency, similar to a modulation of the pump laser power.[13]

We verified that the double slope timing jitter detector is indeed insensitive to AM. For this purpose, we modulated the amplitude of the signal emerging from laser 1 and checked that the difference signal ΔV does not contain any measurable contribution at the modulation frequency. The slope of the discrimination curve was determined as $k=42.5$ ps/V at the operation point.

For a first demonstration that the general principle of baseband-free detection of the field cross correlation is applicable within the context of timing jitter measurements, we measured the residual timing instability of the synchronization between lasers 1 and 2. As a measure for the timing instability, we determined the two-sample standard deviation without dead time $\sigma_x(\tau)$ of the quantity $\Delta x=k\Delta V$, commonly referred to as Allan deviation. σ_x describes the averaged timing deviation as a function of averaging time τ and is plotted in Fig. 4. This timing instability reaches a minimum of about 5 fs at averaging times of several tens of ms. For shorter averaging times, it increases due to technical noise and the limited servo gain of the PLL. At larger τ, mainly the drift of the microwave mixer offset leads to a slightly increased timing deviation of about 10 fs.

The sensitive heterodyne detection of the optical field cross correlation has general potential for various applications besides the timing jitter measurement with the AM-balanced double slope detector presented here. Assuming bandwidth-limited sampling pulses, the detected beat signal represents the gated carrier of the optical signal under consideration, phase-coherently downconverted to the LO frequency and thus providing its modulus and phase. Hence, with a $\pi/2$-phase shifter and two mixers as shown in the gray shaded part of Fig. 2, detection of both the in-phase (Q) and in-quadrature (I) components would be possible. This slight enhancement would add single-shot capability to our setup. Such a device could be used to completely characterize the properties of ultrashort light pulses similar to cross-correlation frequency-resolved optical gating.[14] In contrast, however, it would provide high sensitivity without averaging and thus could be used to monitor and characterize periodically clocked signals such as telecommunication data streams by eye diagrams.

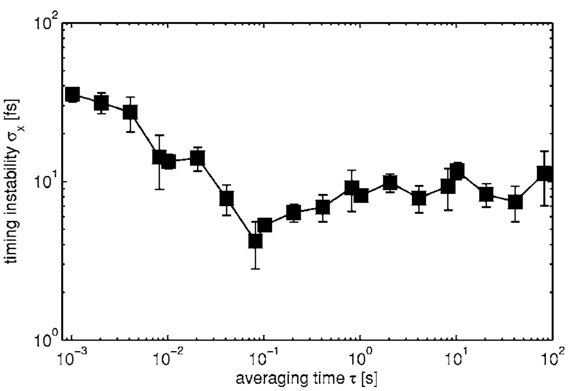

Fig. 4. Timing instability $\sigma_x(\tau)$ as a function of averaging time τ.

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