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A simple and reliable, optical all-fibre, data acquisition trigger signal for fibre-laser asynchronous optical sampling systems

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Abstract

We present an optical all-fibre data acquisition trigger signal particularly suited for fibre-laser asynchronous optical sampling systems. We demonstrate that in the case where the laser spectra are inadequately matched and deliver a weak interferometric signal, post electronic filtering can significantly enhance the signal, removing the necessity for optical band-pass filtering. The method requires no free-space optics and no precise alignment of focused beam spots, eliminating beam pointing stability and walk-off issues.

Keywords: laser measurement applications, ultrafast optics, ultrafast spectroscopy, spectroscopy, time-resolved, THz spectroscopy

(Some figures may appear in colour only in the online journal)

1. Introduction and motivation

Conventional THz time-domain-spectroscopy (THz-TDS) employs a single, sub ps, laser source optically split into a pump and probe beam with a variable time delay provided mechanically. THz asynchronous-optical-sampling (THz-ASOPS) employs two lasers whose pulse repetition frequencies (PRFs) are locked at an offset frequency Δf [1]. The pulse frequency offset causes the time-delay between pairs of pulses from the two lasers to be repetitively ramped between zero and the inverse laser repetition rate at the offset frequency. In both techniques, one laser pulse generates the THz radiation, while the other probes the THz signal. However, THz-ASOPS has the advantages of fast spectrum sweep, high measurement accuracy and femtosecond magnitude time resolution [2]. To achieve high signal to noise in THz-TDS systems a lock-in-amplifier is employed. Conversely, in THz-ASOPS systems the scanning frequency, Δf, is sufficiently high (0.1–10 kHz typically) that multiple data scans may be averaged to increase the signal to noise ratio without resulting in an excessive data acquisition period. However, this necessitates a data acquisition trigger (DAT) signal to initiate each data sweep. For fibre based THz-ASOPS systems it may be considered more convenient to obtain this directly from the control electronics to avoid the necessity of free space optics and attendant problems of laser spot alignment and walk-off present with a two-photon coincidence interaction based on sum frequency generation (SFG) or two photon absorption (TPA) cross-correlation signals [3–5]. However, electronic derived DAT sources suffer from increased error due to intrinsic phase-noise compared with optically derived ones, where the trigger jitter can be cancelled close to the signal [6].

This paper examines an optical all-fibre method of generating a DAT signal based on the interferometric signal generated when two laser pulses, travelling collinearly, overlap temporally [7]. A previous study demonstrating a linear method to detect coincidence between free-space Ti-Sapphire femtosecond lasers employed a 50:50 fibre beam splitter

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coupled with a balanced optical detector. The laser pulses were delivered via 10 m long fibres, chirping the femtosecond laser pulses to over 10 ps duration and demonstrating an advantage of this linear method for coincidence detection, that ultimate accuracy is not constrained by the laser pulse durations but on the difference between the spectral phases of overlapping pulses [8]. However, to achieve a sufficient contrast of the interference signal and hence signal magnitude, two band-pass filters were placed just before the entrance to the optical fibres in order to closely match the two spectra. A further study demonstrated the measurement of waveforms and eye diagrams by optical sampling using coherent detection, employing a mode-locked fibre laser for the sampling pulses and an un-documented data source [9]. Again, the band-width of the fibre laser was reduced in order to match that of the data-signal, with the filter tuned to provide the best spectral overlap between the data and sampling field. Thus, in both cases, attention is paid to closely match the spectra of the two laser fields via the use of optical band-pass filtering enhancing the contrast of the interference signal and hence the signal magnitude. Here, we demonstrate that for a THz-ASOPS system comprising two identical fibre femtosecond lasers, a low power (~1 mW) fibre pick-off is sufficient to deliver a large interferometric signal requiring no optical band-pass filtering. We further demonstrate that in the case of a poor interferometric signal, post electronic filtering can significantly enhance the signal to noise ratio removing the necessity for optical band-pass filtering. The method delivers a robust, optical all-fibre DAT signal that, unlike non-linear methods; requires no initial careful alignment of focussed beam spots, does not suffer walk-off problems and removes the necessity of free-space optics.

2. Principle

Here the time evolution of the ASOPS pump and probe femtosecond laser pulses is simplified to two monochromatic Gaussian pulses $E_m(t)$ and $E_s(t)$ respectively and expressed as follows:

$$E_m(t) = E_m \exp[-t^2/(2T_0^2)\,]\exp(-\mathrm{i}\omega t) \quad (1)$$

$$E_s(t) = E_s \exp[-(t-\tau)^2/(2T_0^2)\,]\exp[-\mathrm{i}\omega(t-\tau)]. \quad (2)$$

With E_m and E_s the peak magnitudes of the two Gaussian pulse electric fields, T_0 the full width at half maximum (FWHM), ω the angular frequency of both Gaussian electric fields and τ the time delay of the probe pulse relative to the pump pulse. While the default initial phase of the two Gaussian electric fields is $\varphi_1 = \varphi_2 = 0$.

The resultant intensity amplitude $I(\tau)$ of the two Gaussian pulses, proportional to $E(t)\,E*(t)$, is expressed as:

$$I(\tau) = E_m^2 \int_{-\infty}^{+\infty} \exp(-t^2/T_0^2)\,\mathrm{d}t + E_s^2 \int_{-\infty}^{+\infty} \exp(-(t-\tau)^2/T_0^2)\mathrm{d}t + 2E_m E_s \cos(\omega\tau) \int_{-\infty}^{+\infty} \exp[(-t^2/2T_0^2) - (t-\tau)^2/2T_0^2]\mathrm{d}t. \quad (3)$$

The FWHM of the laser pulse is 140 fs, while the photodiode response time of the balanced detector (BD) is >2 ns.

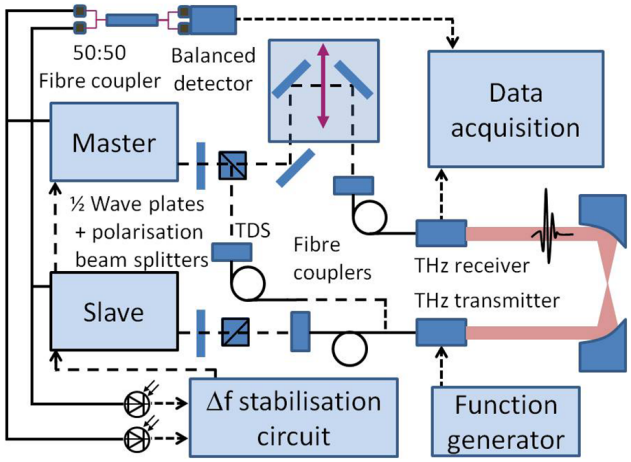


Figure 1. Schematic of combined THz-TDS and THz-ASOPS system.

The current output of the photodiode may thus be considered a simple Gaussian impulse response with peak amplitude proportional to the laser pulse energy. Setting $E_m = E_s = 1$, with $\tau = 0$ initially and then $\tau \geqslant 10T_0$ for equations (2) and (3) gives the ratio of 2:1 for the maximum optical overlap pulse intensity compared with the simple summation of the temporally distinct laser pulses ($10T_0 \leqslant \tau \ll 2$ ns). However in reality, this ratio may be significantly lower due to spectral differences between the two laser pulses. Consequently, a DAT signal can be generated from the optical temporal coincidence of the laser pulses provided a mechanism is available to remove the laser pulse train from the signal. This may be achieved optically via frequency up-shifting the interferometric signal in combination with a suitable optical filter rejecting the longer wavelength laser pulse train, here, it is achieved electronically.

3. Experimental, trigger signal and THz signal acquisition

A combined THz-ASOPS and THz-TDS system comprising two, identical in construction, 100 MHz PRF, 1550 nm wavelength, 140 fs pulse length (FWHM), fibre lasers is depicted in figure 1. The two lasers are off-set frequency locked to an external 10 MHz reference source. A small portion of the laser energy from each laser (<5 mW) is tapped-off before the compensation gratings and split between the control electronics and a 50:50 fibre coupler. The outputs of this coupler are then fed to a nominal 130 MHz bandwidth optical BD (Thorlabs PDB450C). The main output of the two lasers (~200 mW) feed into free-space compensation gratings before being coupled into fibre couplers via power splitters. The spectra of the two lasers are matched with the use of an optical spectrometer and the temporal pulse widths minimised with the aid of an auto-correlator.

To demonstrate the interferometric signal (figure 2) a 750 MHz bandwidth integrated photodiode and single-end (0 to −3.5 V) transimpedance amplifier (TIA) fed via a 2:1 fibre coupler replaces the THz antenna and receiver in figure 1.

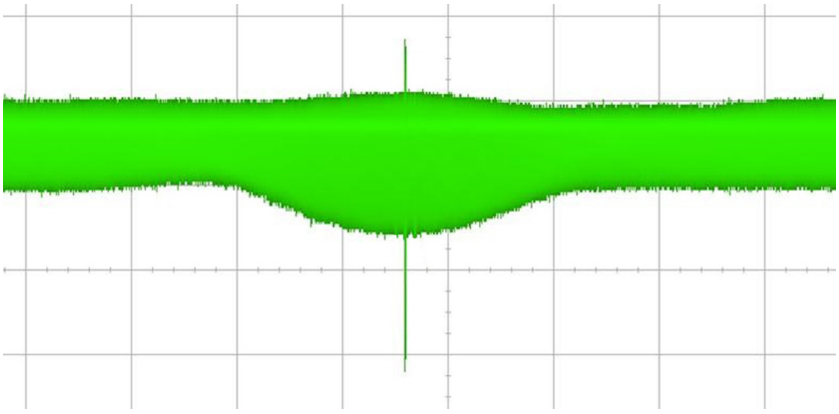


Figure 2. Interferometric signal, 20 mV/div, 20 μs/div, 5 kHz Δf.

Evident in figure 2 is the laser pulse train and the simple summation of the temporally distinct pulses ($\tau < 2$ ns) adjacent to the coherent interference signal. The relative temporal phases of the two lasers spectra are sufficiently matched by the compensation gratings to achieve a short interaction period of ~500 fs with a ratio approaching 2:1 for the peak interference signal compared with the simple intensity summation of the temporally distinct pulses ($\tau < 2$ ns). It is possible, but not optimum to use this arrangement for a DAT signal as the coherent interaction between the pump and probe pulses can result in constructive or destructive interference (equations (2) and (3) and setting the trigger point above the simple summation amplitude will miss the coincidence events masked within the non-coherent signal. However, in the case of the four port 50:50 fibre beam-coupler of figure 1, each laser pulse intensity is shared equally between the two paths of the beam-coupler and this common signal is cancelled at the BD. This efficiently removes the laser pulse train irrespective of the relative pulse intensities of the two lasers to leave a large (>6 V, pk/pk) interference signal generated whenever a coincidence event occurs—top trace figure 3.

Antonucci *et al* [5] noted that a trigger threshold set at 40% of the maximum signal allows the detection of roughly 70% of all coincidence events, here, the threshold may be set far lower capturing the majority of all coincidence events. However, in figure 3, only positive signals contribute to coincidence detection. Utilising both positive and negative going signals can be achieved by squaring the signal, for example using the AD835 I.C. from Analog Devices. Even so, not all coincidence events may be detected by this method as some will remain undetected if the carrier-envelope phases (which are not controlled here) result in the two pulses being in near quadrature. To overcome this requires the implementation of a dual-quadrature interferometer [9], nevertheless, the advantage of this far simpler set-up more than compensates for the small reduction in the rate of coincidence detection. Evident in the top trace of figure 3 is the presence of a disparity in the chirp of the two lasers spectra, with the longer wavelengths interfering at the front of the temporal overlap and the shorter at the tail (to visualise this, consider the case where the chirp is identical or zero and where only one is chirped). The interaction period has also increased to ~3 ps, again a consequence of the temporal miss-match in the spectral phases of the two lasers.

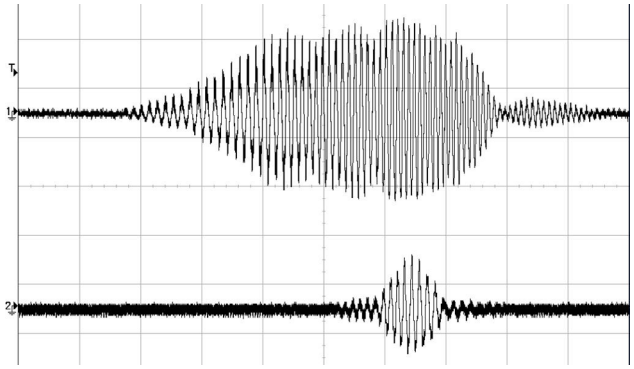


Figure 3. Interferometric signals (see text), 2 V/div, 500 ns/div, 100 Hz Δf, average laser powers ~1 mW.

THz-ASOPS systems employing two identical lasers deliver spectra sufficiently well matched to generate a large interferometric signal. However, in the case where the spectra are not well matched this may be difficult to achieve if the low contrast of the interference signal and hence low magnitude adds to the fact that 50:50 fibre beam-couplers and BD input coupling are not sufficiently exact. To highlight the problem the spectra of the two lasers are deliberately miss-matched by detuning the lasers optical cavities and the results displayed in figure 4.

The top two traces are, respectively, the individual non-inverted and inverted signals from the BD and display significantly reduced interferometric signals in comparison with figure 2. The combined signals of the third trace (short time scale) and fourth trace (long time scale) now exhibit an appreciable relative pulse train amplitude, which will mask smaller magnitude coincidence event signals. Previous studies avoid this by introducing optical band-pass filtering as discussed in section 1, here a different approach, post electronic filtering, is presented. Examining the upper interferometric signal of figure 3 reveals that the signal frequency varies from ~16 MHz to ~22 MHz front to back. This is significantly lower than the 100 MHz PRF of the lasers and indicates that a suitable electronic low-pass filter employed at the BD output will selectively suppress the laser pulse train signal. The bottom trace of figure 4 displays such a signal using the inline low-pass passive filter BLP-70+ from Mini-Circuits. A higher-order band-pass filter centred at 20 MHz would further improve

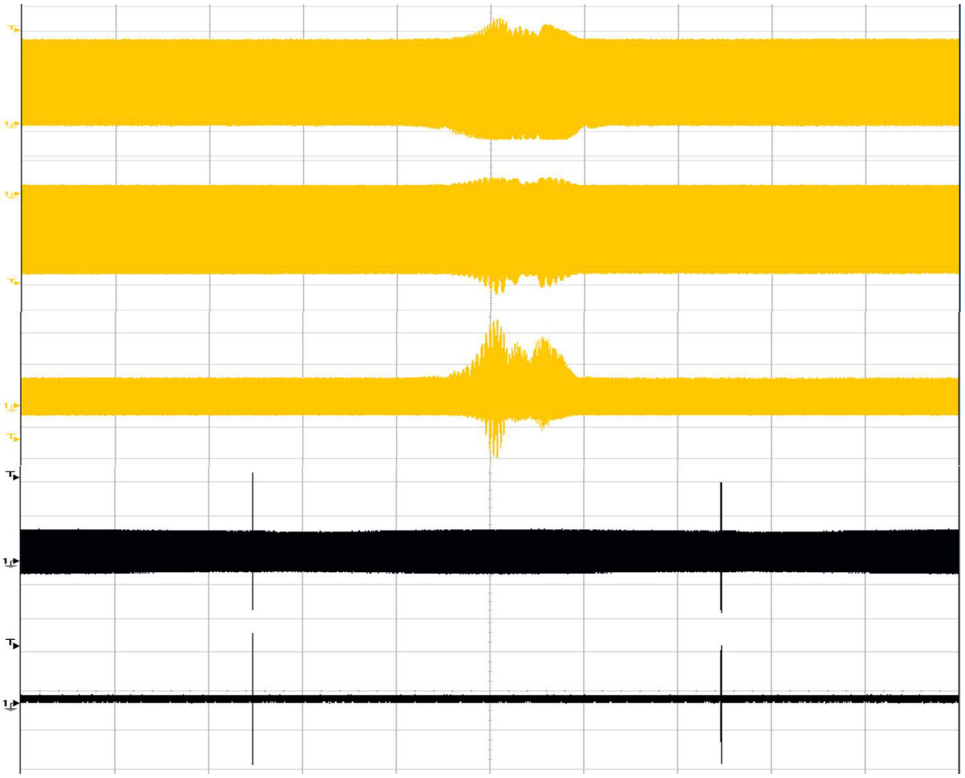


Figure 4. Interferometric signals: Top, non-inverted BD output. Second, inverted BD output. Third, combined BD output. All 1 V/div, 20 μs/div. Fourth, combined BD output. Bottom combined BD and low-pass-filter output, both 1 V/div, 20 ms/div. $\Delta f = 10$ Hz all.

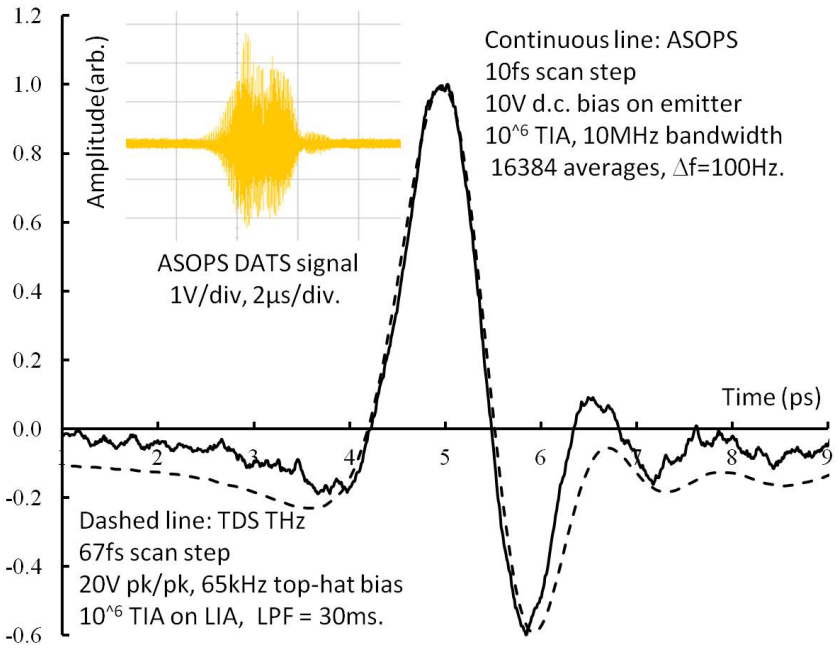


Figure 5. TDS and ASOPS THz scan: THz emitter and receiver BATOP PCA-100-05-10.

signal to noise. Electronic filtering is the more simple option to consider before resorting to optical band-pass filtering and may be sufficient in most instances.

Replacing the integrated photodiode and TIA (see figure 2) with a second BD (in-house) and a low-pass filter while using only one input, the lower interferometric signal of figure 3 is obtained, demonstrating the effectiveness of electronic band-pass signal filtering. Matching the chirp of the two lasers by adjusting the compensation gratings yields a short interaction time of 500 fs. Note that the uniformity of the signal period also indicates that the relative temporal phases of the two lasers spectra are well matched. To quantify the trigger timing a Schmitt trigger is added to the in-house BD. With Δf set to 100 Hz and triggering off the Thorlabs BD output, averaging the Schmitt trigger signal over 16 384 scans broadens the initial 5 ns risetime to 68 ns (10:90%

measured on an oscilloscope), indicating a trigger error of 63 fs in the scan domain. Given that the laser pulse lengths are 140 fs this value appears excessive and is a consequence of the temporal miss-match in the spectral phases of the laser pulses delivered to the Thorlabs BD. Adjusting the relative fibre lengths would address this and transform the long interaction period evident in the top trace of figure 3 to the much shorter one of the lower trace, reducing the trigger error to below 20 fs.

Finally, a direct comparison may be made between a THz-ASOPS signal acquisition employing an interferometric DAT signal and one obtained via scanning THz-TDS using the experimental set-up detailed in figure 1. For the THz-TDS scan a Stanford Research Systems SR830 lock in amplifier was used to acquire the signal. The translation full scan length was 6 mm, with 20 ± 1 μm or 67 ± 3.4 fs round-trip scan steps. Laser power was stabilised within 1% over both the THz-ASOPS and THz-TDS scan period. For the THz-ASOPS signal a 500 MHz digital oscilloscope averaged the amplified signal from an, in-house, transimpedance amplifier. The THz-ASOPS signal was temporally coincident with the DAT signal. The combination of a low 5 nA peak THz signal and amplification only to the mV level required high averaging to achieve acceptable signal to noise. The two normalised signals and parameters are displayed in figure 5. No discernible signal broadening is present in the THz-ASOPS scan compared with the THz-TDS signal, demonstrating that the interferometric DAT signal performs satisfactorily.

4. Conclusion

We have demonstrated that for a THz-ASOPS system comprising two identical fibre femtosecond lasers, a low power (~1 mW) fibre pick-off is sufficient to deliver a large interferometric DAT signal requiring no optical band-pass filtering. We further demonstrate that in the case where the laser spectra are inadequately matched and deliver a weak interferometric signal, post electronic filtering can significantly enhance the signal to noise ratio removing the necessity for optical band-pass filtering. The method delivers an optical, all-fibre, ASOPS DAT signal with timing error of 63 fs for a 100 MHz PRF, 140 fs laser pulse length, 1550 nm fibre THz-ASOPS system with potential to further reduce this to below 20 fs. The technique easily delivers a large signal to noise and volt level DAT signal that requires no initial careful alignment of focussed beam spots and does not suffer beam walk-off problems. It is particularly suitable for fibre coupled antenna THz-ASOPS systems as it completely removes the necessity for free-space optics.

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