Compact implementation of Fourier transform two-dimensional IR spectroscopy without phase ambiguity

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Abstract

We describe an optimized setup for two-dimensional (2D) IR spectroscopy, which can be implemented at low additional cost and with standard optics in any laboratory equipped for femtosecond mid-IR spectroscopy. An interferometer produces a pair of intense pump pulses, whose interferogram is simultaneously recorded and directly yields the relative phase needed for the calculation of absorptive 2D spectra. We analyze different sampling methods based on a realistic noise model and introduce fast population time modulation as an alternative to the use of choppers in the suppression of scatter. Signal levels are compared to those of a photon-echo setup.
A compact implementation of Fourier transform 2D-IR
spectroscopy without phase ambiguity

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We describe an optimized setup for two-dimensional infrared spectroscopy, which can be implemented at low additional cost and with standard optics in any laboratory equipped for femtosecond mid-IR spectroscopy. An interferometer produces a pair of intense pump pulses, whose interferogram is simultaneously recorded and directly yields the relative phase needed for the calculation of absorptive 2D-spectra. We analyze different sampling methods based on a realistic noise model and introduce fast population time modulation as an alternative to the use of choppers in the suppression of scatter. Signal levels are compared to those of a photon echo setup.

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1. Introduction

During the past decade two-dimensional spectroscopy has developed from a challenging experiment for specialized laser laboratories into a sensitive tool for the investigation of chemical, physical and biological systems[1–11]. Two-dimensional infrared spectroscopy (2D-IR) was initially devised as a narrow band pump - broad band probe experiment[12]. It is most versatile in a photon echo configuration, with full intensity and polarization control over each individual field in the non-linear mixing process[13, 14]. Here, phase stability and precise knowledge of the relative phase of the laser fields at the sample is necessary to separate absorptive and dispersive signals and to achieve the highest possible spectral resolution and information content[15, 16]. Since 'phasing' and phase control are not required when recording the intrinsically absorptive 2D-IR spectra by the frequency-domain pump-probe method, this original version of 2D-IR involves much less experimental effort[17], and has thus remained attractive[18, 19], despite its lower time- and spectral resolution as well as lower sensitivity. The pump-probe experiment is also insensitive to phase shifts introduced, for example, by an additional laser beam that triggers a photoreaction. The recording of absorptive transient 2D-IR spectra is thus relatively straightforward in this experimental arrangement[20].

Already many years ago Wiersma and co-workers explored the close relationship between a heterodyne-detected photon echo and a Fourier transform pump-probe experiment with a collinear pair of pump pulses[1], and their formal analogy was analyzed by Faeder and Jonas [21]. Since then it has been demonstrated both in the infrared[22, 23] and the visible[24, 25] spectral range that the latter method can combine many advantages of the photon echo and the frequency domain 2D techniques. A collinear pump-geometry has recently also been employed to record two-dimensional THz spectra[26]. DeFlores et al. used a Mach Zehnder interferometer to produce a mid-IR pump pulse pair and dispersed the second output of the interferometer to calibrate the time delay between them[22]. Zanni and co-workers generate the pulse pair with the help of a pulse shaper, which has the advantage that their relative phase is exactly known and can be varied at wish[27]. Here we build on the interferometer method of the Tokmakoff group[22], and present a compact setup that is much simpler than a pulse-shaper but still allows us to automatically phase the 2D-IR spectrum. A HeNe laser continuously tracks the delay changes between the pump pulses. The second mid-IR output of the interferometer is used to repeatedly record interferograms of the pump pulse pair,
from which their relative phase is uniquely determined.

The scope of this paper is to present and discuss all necessary practical details for the construction and operation of what we believe is the most simple, yet fully functional Fourier transform 2D-IR experiment without phase ambiguity. This includes of course several concepts which have been previously described in the cited literature.

2. Motivation

The main difference between a third order photon-echo and a pump-probe experiment is the fact that the time-ordering of the first and second field interactions is unknown in the former, while it is uniquely defined by the direction of the echo signal in the latter (see Fig. 1). This makes it possible to separately measure different Liouville space pathways. In particular, contributions arising from so-called 're-phasing' diagrams, characterized by oscillations of opposite phase during the two coherence time periods, and 'non re-phasing' diagrams (same oscillation phase during the two coherence times) can be distinguished. However, in order to obtain absorptive line shapes, which yield the highest spectral resolution, both contributions must be added[15]. In practice, the coherence time \( t_1 \) is thus scanned twice, with inverted time ordering of pulses (1) and (2). In a pump-probe geometry with a collinear pair of pump pulses, on the other hand, the same 're-phasing' and 'non re-phasing' signals are emitted simultaneously into the direction of the probe beam and \( t_1 \) needs to be scanned only once. Furthermore, the probe beam also acts as the 'local oscillator' (LO), which interferes with the emitted third order polarization for heterodyne detection, whereas a separate LO beam is needed in the echo geometry. This considerably reduces the experimental effort of 2D-IR spectroscopy to the optimization of a single overlap and the determination of the relative phase of two collinear mid-IR pump beams.

3. Set-Up

In practice, the 2D experiment only requires the addition of an interferometer to a standard mid-IR pump probe setup as shown in Fig. 2 A. Probe and reference beams are small reflections of the mid-IR OPA output generated by a wedged CaF\(_2\) window (brown line in Fig. 2). Their diameter is enlarged by a factor of 1.5 in a telescope and they are tightly focused (70\(\mu\)m FWHM) onto different spots on the sample, dispersed in a monochromator and detected by a double array MCT detector with 32 pixels. The main fraction of the mid-IR light (orange lines in Fig. 2) enters a Mach-Zehnder interferometer (total footprint 16 \(\times\) 16
cm\(^2\) . The beams in the two interferometer arms experience the same material dispersion (inside the beamsplitters BS1 and BS2) as well as two gold mirror reflections (M1,M2 and M3,M4). We use the interferometer output generated by a single beamsplitter reflection per beam in order to excite the sample. The two pump pulses thus have identical energies, independent of the exact beamsplitter reflectivity (nominally 50\%). They are focused to a spot size of \(\approx 100\mu m\) FWHM in spatial overlap with the probe beam. The second interferometer output is collimated onto a pyroelectric detector (at room-temperature) in order to record a linear pump pulse interferogram during every interferometer scan with the help of simple sample-and-hold electronics.

We do not collect data on a predefined grid of time points, but continuously move the interferometer arm during data acquisition, and trace the delay changes with a HeNe laser beam. The HeNe beam propagates approximately 2 cm on top of the IR-beam inside the interferometer (red dotted lines in Fig. 2). It is reflected by the same moving mirrors as the mid-IR beam (M1,M2), but we use separate beamsplitters. Each pair of mid-IR and HeNe beamsplitters are firmly fixed to the same mount, while a pair of adjustable gold mirrors for each beam (attached to a single base) in the static arm allows us to separately optimize mid-IR (M3,M4) and HeNe (M3’,M4’) overlap, without loosing the necessary stability of the interferometer. For example, optimal overlap and interference of the mid-IR pump pulses is simply achieved by separately optimizing a pump-probe signal when blocking the static arm (and tuning the external mirror M5) and the moving arm (and tuning mirror M4) of the interferometer. Only slight re-adjustments are necessary even after realigning the OPA.

In order to establish an equidistant time grid, we count the number of fringes of the HeNe laser interferogram and sort the mid-IR data according to the fringe number (bin) at the instant of pulse emission. All data within a given time bin is averaged. This is equivalent to a convolution of the time-domain signal with a narrow square window function or multiplication of the frequency-domain signal by the corresponding Fourier transform, which is exactly known (a sinc function) and varies only slowly with wavelength in the mid-IR.

In the simplest form of measurement, the interferometer is scanned relatively slowly (e.g. 2 fs delay in 5-10 ms), corresponding to a few pulsed laser triggers per HeNe fringe. It is thus possible to record the HeNe laser interferogram with a single photodiode and digitize this signal at the same rate and with the same AD card that is used for mid-IR data acquisition.
Fringe counting can be done in the computer and yields a precise measure of the monotonous delay changes during a single $t_1$ scan. Since the absolute delay can be recovered for each individual scan from the simultaneously recorded interferogram of the mid-IR pump pulses (see below), multiple forward and backward scans can be averaged.

Faster scans require a fringe counting scheme that is not limited by the repetition rate of the femtosecond laser or the relatively slow data acquisition card. In addition, bin numbers must be determined reproducibly, since the mid-IR interferogram of a single fast scan is no longer sufficient to correct for shifts. In this case we use a stand-alone quadrature counting method based on refs. [28, 29]. A $\lambda/4$ waveplate is inserted into the HeNe beam in the static arm of the interferometer, producing circular polarization. The sum of the circular polarized beam and the linear polarized beam from the moving arm is split into two perpendicular polarized components by a polarization cube oriented at 45 degrees relative to the incident polarization (see Fig. 2 C). The two signals have a relative phase difference of 90 degrees and are used for continuous quadrature counting of the HeNe fringes at arbitrary speed and direction of delay changes. Only the fringe numbers at the instant of the femtosecond pulse emission are read by the computer synchronous with the mid-IR data, which is averaged in the corresponding time bin. A detailed scheme of the very compact counting and pyro-detector electronics is available from the authors and will be developed into a kit for interested laboratories.

For scanning the $t_1$ time we use a small DC-motor (PI M-111-1.DG) with rotary encoder, which is not precise enough to sample a sufficiently equidistant time-grid. Both our fast and slow HeNe fringe counting schemes, however, allow for efficient, unbiased averaging of data in time bins of the duration of a HeNe oscillation period (2.11 fs), which eliminates any spectral artifact that may arise from imperfect motor motion. To ensure a uniform sampling of the time bins, we even add random delays to the motor starting position of each $t_1$ sweep. Much simpler linear motor stages should thus be equally suitable.

4. Phase Determination and Signal Processing

The absolute delay between the two pump pulses and their relative phase is determined to very high precision in a way similar to the method used in FTIR spectrometers.

Starting from an approximate time zero (a sampling point or time bin $k = k_0$ close to the maximum of the pump pulse interferogram $I(t_1)$ shown in Fig. 3 A), a discrete Fourier
transform yields a spectral amplitude and phase:

\[
A(\omega_1[j]) = \sum_{k=1}^{N} I(t_1[k]) \exp\left(-2\pi i \left(\frac{k - k_0}{N} \right) (j - 1)\right) \\
= |A(\omega_1[j])| \exp(i\phi_{k_0}(\omega_1[j]))
\] (1)

In order to perform this operation with automated FFT routines the first \(k_0 - 1\) points of the list \(I(t_1[k])\) have to be shifted to the end.

The slope of the phase \(d\phi_{k_0}/d\omega_1\) near the maximum of the spectrum is negative if \(k_0\) is chosen too small and positive if \(k_0\) is chosen too large (see the dotted lines for \(k_0 = 99\) and \(k_0 = 113\) in Fig. 3B). This offers a precise way to find the sampling bin \(K\) closest to delay zero in an iterative search. \(K\) and the associated, spectrally flat phase factor \(\phi_K\), which is needed to compute the real part of the 2D spectrum can thus be determined automatically by the computer during data acquisition. For the data shown in Fig. 3, \(K = 106\), and \(\phi_K = -0.263\) is the offset of the corresponding almost horizontal solid line in part B.

The MCT array detector measures the probe-beam intensity as a function of frequency \(\omega_3\), coherence time \(t_1\) and waiting time \(t_2\), which is a sum of several contributions[21, 25]:

\[
S(\omega_3, t_2, t_1) \propto |E_{\text{probe}}(\omega_3) + i\omega_3 P^{(1)}(\omega_3) + P^{(3)}_{pp}(\omega_3, t_2) + P^{(3)}_{pp2}(\omega_3, t_2, t_1) + P^{(3)}_{2D}(\omega_3, t_2, t_1)|^2
\] (2)

The spectral density of the probe pulse and linear absorption (linear polarization \(P^{(1)}(\omega_3)\)) are normalized out by dividing by the reference signal. The pump-probe signal due to the third order polarization generated by two field interactions with the same pump pulse \(P^{(3)}_{pp}(\omega_3, t_2, t_1)\) are either static (pulse 1) or change only slowly (pulse 2) as a function of coherence time \(t_1\) (they are not oscillatory) and are eliminated by Fourier transformation. In the absence of scattering, the absorptive 2D signal is thus directly obtained from the discrete Fourier transform:

\[
S_{2D}(\omega_3, t_2, \omega_1[j]) = Re \left[ \Delta t \sum_{k'=1}^{N'} S(\omega_3, t_2, t_1[k' + K - 1]) \exp\left(-2\pi i \left(\frac{k' - 1}{N'} \right) (j - 1)\right) - i\phi_K \right]
\] (3)
where $\Delta t$ fs is the width of the time bins, $\phi_K$ is the relative phase between the two pump pulses at $t_1 = t_1[K]$, determined from the pump pulse interferogram. $\mathcal{S}(\omega_3, t_2, t_1[k])$ is the probe intensity of Eq. 2, recorded at the spectrometer frequency $\omega_3$ in the time bin $k$, divided by the corresponding intensity of the reference beam. This division greatly improves signal to noise and corrects for the finite width of the probe spectrum. Zeropadding can be used to make $N' = N$ of Eq. 1 in order to obtain the same frequency grid.

The 2D signal calculated using Eq. 3 can also be automatically corrected for the effects of averaging the data in coherence time windows of one HeNe laser period, as well as for the finite width of the pump pulse spectrum: The binning of data in the time-domain corresponds to a multiplication of the frequency domain spectra by the Fourier transform of a square of width $\Delta t = 2.11$ fs:

$$I_{\text{bin}}(\omega_1) = \frac{\sin(\Delta t \omega_1)}{2\pi \Delta t \omega_1}. \quad (4)$$

This sinc function is shown as a dashed line in Fig. 3 B. Furthermore, the response of the pyroelectric detector is practically wavelength-independent, so the spectrum of the pump pulses at the sample is directly given by the amplitude of the Fourier transform of the mid-IR interferogram. As this is recorded on the same time grid as the actual data, it already contains the effect of data binning. A corrected 2D spectrum, corresponding to a measurement with infinitely broad pump and probe pulses is thus obtained by dividing Eq. 3 by $|A(\omega_1)|$. It is easily seen from Fig. 3 B, that data binning has a negligible effect compared to the limited spectral width of the pump pulses, which is often not corrected for in the literature.

Note that the imaginary part of the Fourier transform in Eq. 3 does not yield the dispersive part of the 2D-IR spectrum. In fact, the signal $\mathcal{S}(\omega_3, t_2, t_1)$ is in principle fully symmetric with respect to $t_1$, such that the imaginary part of its Fourier transform should vanish. However, we have to restrict the FT to positive coherence times because this symmetry is broken by the population time dependence of $\mathcal{S}(\omega_3, t_2, t_1)$. If the full complex 2D spectrum is desired, it must be computed from the absorptive spectrum via a pseudo Kramers-Kronig transform, as outlined for example in [25].
5. Practical Aspects of Data Collection

A. Fast versus Slow Interferometer Scanning

The simplest form of operation of our setup, based on the simultaneous digitization of the HeNe-laser photodiode and mid-IR signals requires relatively slow changes of the coherence time (approximately 10 seconds for a $t_1$ scan of 3 ps). In order to normalize out slow intensity fluctuations we then need to chop one or both of the pump pulses at half the laser repetition rate. To calculate the 2D signal $\mathcal{S}$ in Eq. 3 is replaced by the ratio $\mathcal{S}_{\text{pump on}}/\mathcal{S}_{\text{pump off}}$. Taking the ratio instead of the difference corrects for different probe and reference beam intensities and the different response of individual detector elements. Without chopping $\mathcal{S}(\omega_3, t_2, t_1[k])$ should be divided by its average over all $t_1[k]$ for the same reason.

Much higher scan speeds are possible when we use the independent quadrature counting scheme for delay tracking. It is then possible to fully exploit the relatively long-lived intensity correlation of the mid-IR pulses, which in our system decays with a time constant of approximately 60 ms (probe divided by reference intensity after gated integration and digitization). A scan speed corresponding to Nyquist sampling (four points per mid-IR optical cycle) thus yields a very high degree of correlation in the spectral window of interest, and a single $t_1$-scan of 3 ps at $\lambda = 5 \mu m$ now only requires 0.4 seconds. However, in order to uniformly record data in all time bins, multiple scans are needed.

In Fig. 4 we compare, for the different scan modes, spectra computed from simulated interferograms, based on realistic motor motion (monotonic with random deviations from linear) and a realistic noise model, with an exponential intensity correlation decay of 60 laser triggers (see Appendix B for details). Each of the four signals corresponds to approximately 32000 triggers. This data is ‘collected’ in 2 back and forward scans over 6 ps at slow scanning speed and 40 scans at high scanning speed, equivalent to 5-8 data points in total per time bin. The advantage of chopping in the slow scan mode (Fig. 4 A and B) is clearly visible. Even more striking is the signal to noise enhancement when the scan speed is increased by a factor of 20 to approximate Nyquist sampling (Fig. 4 C and D). In the fast scans, however, the chopper is no longer useful, as it reduces the effective correlation between subsequent sampling points in addition to reducing the averaging statistics by a factor of two.
B. Scattering suppression

When a fraction $\beta$ of the pump beams reaches the MCT detector because of scattering, the extra term in Eq. 2 gives rise to the additional signal

$$S_{\text{scatter}}(\omega_3, t_2, t_1) \propto |E_{\text{probe}}(\omega_3) + \beta[E_{\text{pump}1}(\omega_3, t_2) + E_{\text{pump}2}(\omega_3, t_2, t_1)]|^2.$$  

The contribution due to $E_{\text{pump}2}$ can be eliminated by chopping the static arm of the interferometer, while the interference between the static pump pulse 1 and the probe beam is eliminated by the $t_1$ Fourier transform [22]. When $|E_{\text{probe}}| \gg \beta |E_{\text{pump}}|$ the remaining term proportional to $\beta^2 |E_{\text{pump}}|^2$ can be neglected.

If no chopper is used in fast interferometer scans, an alternative strategy to suppress scattering background must be found. An elegant solution is to periodically invert the relative phase between the pump pulses and the probe pulse. With a pulse shaper generating the pump pulses, a pure phase inversion is possible [27]. This changes only the sign of the scattering contribution, but not that of the desired third order polarization. Scattering is thus eliminated by adding the two data sets. In the much simpler interferometer setup, a pseudo phase inversion can be achieved by changing the population time $t_2$ by half a period of the mid-IR carrier frequency $\omega_0$ [30]. However, adding data recorded for two population times $t_2 \pm \pi/(2\omega_0)$ fully eliminates only the scattering at the center frequency of the laser pulse. As shown in Appendix A, scattering suppression of more than two orders of magnitude over 10% bandwidth (e.g. a spectral window of 200 cm$^{-1}$ at 5 \(\mu\)m) is nevertheless possible by adding data recorded at population times $t_2$ (with double weight) and $t_2 \pm \pi/\omega_0$. In our current setup this is achieved by modulating the population time at one quarter of the laser repetition rate, using a photoelastic modulator, to which the laser is synchronized [31] (‘phase shifter’ in Fig. 2 A). As a much simpler alternative, a librating Brewster window can be inserted into the pump or probe beam [32]. An illustration of the power of this method is shown in Fig.5 for a strongly scattering sample.

C. Signal size

The third order polarization is proportional to the product of all three excitation fields. In an echo setup, these are ideally all equal so the echo intensity is proportional to $(\sqrt{I_0/3})^3$, where $I_0$ is the total available mid-IR intensity (after splitting off the weak local oscillator beam). In the pump-probe geometry the third excitation field is provided by the probe pulse, and
the corresponding polarization is proportional to \( \sqrt{I_{\text{probe}}} \times \sqrt{I_{\text{pump1}}} \times I_{\text{pump2}} \). Like the local oscillator in the echo setup, the probe beam is usually a small reflection of a CaF\(_2\) or ZnSe window with an intensity \( I_{\text{probe}} = \alpha I_0 \). Using conventional 50\% beamsplitters, only half of the light entering the interferometer is directed onto the sample, so \( I_{\text{pump1}} = I_{\text{pump2}} \approx I_0/4 \). As a result the ratio of echo intensity and (pump-probe) polarization is:

\[
\frac{S_{\text{echo}}}{S_{\text{pump-probe}}} \approx \frac{1}{4\sqrt{\alpha} \left( \frac{1}{\sqrt{3}} \right)^3} \approx \frac{0.77}{\sqrt{\alpha}}
\]  

(6)

For a typical value of \( \alpha = 0.04 \) (CaF\(_2\)-window) the echo intensity is thus approximately four times larger than the corresponding polarization in the pump-probe geometry. Increasing \( \alpha \) usually brings no improvement, since in the pump-probe geometry the local oscillator is identical with the probe beam, and additional filters, which are then needed to prevent detector saturation, attenuate both the local oscillator and the emitted polarization. In contrast, in the echo setup, the local oscillator can be attenuated independently, without weakening the echo. As a consequence, the heterodyned 2D-IR signal in the pump-probe geometry is weaker than that recorded in the echo-geometry by another factor \( \sqrt{10^{-OD}} \), where \( OD \) is the optical density of the filter(s) placed between sample and detector. Depending on the sample transmission this factor typically lies between 3-10 (OD 1- OD 2) for our nitrogen-cooled MCT array detector with \( \alpha = 0.04 \).

This significant difference in sensitivity is partially compensated by the simultaneous collection of rephasing and non-rephasing signals. In addition, a higher optical density of the sample, which also leads to re-absorption of the third order polarization, can lead to a larger signal increase in the pump probe geometry, when it allows to remove filters in front of the detector. Tighter focusing is also more straightforward in the self-heterodyning pump-probe method. Furthermore, as pointed out by Zanni and coworkers, polarization can be used to independently control the strength of all four fields even in the pump-probe geometry [34]. In the interferometer setup an orthogonal polarization of the two pump pulses can be achieved by replacing the beamsplitters by polarizers. The full incident intensity (minus a small leakage needed for recording the pump pulse interferogram) is then available for the excitation of the sample. A third polarizer is placed behind the sample and blocks most of the probe beam, but fully transmits the polarization which is polarized orthogonal to it. It is thus possible to work with the same beam intensities as in an echo experiment without the need of filters between sample and detector, and to achieve the same signal size and
sensitivity. Compared to a 2D-spectrum recorded with all field polarizations parallel, the diagonal signals are smaller by a factor 3, while the cross peaks are often enhanced.

6. Conclusion
The pump-probe geometry with two collinear pump pulses has in the recent past lead to greatly simplified Fourier transform 2D experiments, which require only two laser beams and knowledge of a single phase factor in order to obtain absorptive spectra. In the visible spectral range pulse shapers which can generate the pump pulse pairs with a well-defined phase difference are already commercially available. In the mid-IR, however, a significant amount of expertise is still needed for their construction and operation, and light losses weigh heavier owing to weaker sources and signals. Here we have shown that a much simpler interferometer, combined with delay tracking and the removal of the phase ambiguity can perform similarly well. In particular, an interferometer is compatible with fast coherence time scanning and efficient scattering suppression, which are important strengths of active phase control in the pump probe geometry. Broad band beamsplitters allow for quick wavelength changes without significant re-alignment. When equipped with polarizing beamsplitters (such as grid polarizers) the interferometer-based pump-probe experiment can in principle even achieve the same sensitivity as an optimized echo setup. However, we see the main advantages of the interferometer technique in its relatively simple implementation and easy use, which should help to make 2D-IR a much more widespread spectroscopic probe. The adaptation of the method for different frequency ranges, such as the far infrared, may be equally promising.

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Appendix A: Scattering suppression by population time modulation

The main background in a 2D spectrum often arises from scattering, i.e. when a small amount of light of one or several pump pulses reaches the detector and interferes with the probe (or local oscillator). In a pump probe-configuration, the scattering signal as a function of probe frequency $\omega_3$ and delay $t$ between pump and probe pulse is given by

$$sc_0(\omega_3, t) = \frac{|E_{\text{probe}} + E_{\text{scatter}}|^2}{|E_{\text{probe}}|^2} = 1 + \beta'^2 + 2\beta' \cos(t\omega_3 + \psi).$$

where $|E_{\text{scatter}}|/|E_{\text{probe}}| = \beta' << 1$ and $\psi$ is the phase difference between the electric fields of the pump and probe pulse when their envelopes overlap exactly. The time-independent term $1 + \beta'^2$ is eliminated by the $t_1$ Fourier transform, but the time and frequency-dependent term $2\beta' \cos(t\omega_3 + \psi)$ can become very large; if only 0.1% of the pump light is scattered onto the detector, the scattering signal is of the same size as a 5 mOD absorption change, i.e. much larger than many 2D signals of interest.

The idea of population time modulation is to mimic, by a corresponding shift of $t$, a carrier envelope phase change from $\psi$ to $\psi + \pi$. The latter is only possible with a pulse shaper and completely inverts the scattering signal at all probe frequencies without affecting the third order polarization. At a selected probe frequency $\omega_0$ the same is achieved by changing the population time form $t - \frac{\pi}{2\omega_0}$ to $t + \frac{\pi}{2\omega_0}$. After averaging over the signals recorded at these two time delays we are left with a scattering contribution of

$$sc_1(\omega_3, t) = \frac{1}{2}[sc_0(\omega_3, t - \frac{\pi}{2\omega_0}) + sc_0(\omega_3, t + \frac{\pi}{2\omega_0})] = 1 + \beta'^2 + 2\beta' \cos(\omega_3 t + \psi) \cos(\frac{\pi \omega_3}{\omega_0}).$$

(8)

We see that $sc_1$ and $sc_0$ are exactly of the same form so we can generalize:

$$sc_n(\omega_3, t) = \frac{1}{2}[sc_{n-1}(\omega_3, t - \frac{\pi}{2\omega_0}) + sc_{n-1}(\omega_3, t + \frac{\pi}{2\omega_0})] = 1 + \beta'^2 + 2\beta' \cos(\omega_3 t + \psi) \cos^n(\frac{\omega_3}{\omega_0}).$$

(9)

which means that scattering can in principle be suppressed to arbitrary order around a central frequency $\omega_0$ by averaging data recorded at population times in steps of $\frac{\pi}{2\omega_0}$. The scattering contribution left after $t_1$ Fourier transform is due to the moving arm of the interferometer, so $t = t_2 + t_1$. The
appropriate weights given by Pascal’s triangle. First \( n = 1 \) and second order \( n = 2 \) averaging are the most useful, since they are compatible with fast delay modulation, as illustrated in Fig. 6 B. Photoelastic modulators or ZnSe plates driven to perform librations at Brewster angle can be used to induce such population time shifts at the kHz repetition rate \( f_{\text{rep}} \) of the laser. For higher order modulation \( n > 2 \) a combination of at least two delay modulators at different frequency and amplitude would be necessary (e.g. green line in Fig. 6 B). When needed, scattering suppression to third order is thus more easily achieved by combining second order delay modulation with a slow delay change of \( \pi/\omega_0 \). Slow delay dithering is already used in many laboratories for the reduction of scatter contributions to 2D-IR spectra. However, it is usually much less efficient than fast modulation due to phase drifts and insufficient delay motor precision.

It should be noted that neither delay modulation nor chopping of the static beam reduce the higher order contribution from interference of scattered light of one pump beam with that of the other. When this becomes significant, measurements should be carried out with perpendicular polarized pump pulses.

Appendix B: Details of the numeric simulations

The parameters used in the simulations shown in Fig. 4 were chosen to mimic the performance of our our setup. Each probe pulse intensity is normalized by the corresponding reference pulse, yielding a series of data points

\[
(I_{\text{probe}}/I_{\text{ref}})[i] = \text{const} + \text{sig}(t[i]) + a_{\text{noise}} \Delta I[i]
\]

(10)

Normally distributed noise with a standard deviation of one and an exponential correlation decay \( 1/\kappa = 1/60 \) (laser triggers) is generated with the help of the equation

\[
\Delta I[i+1] = \Delta I[i](1-\kappa) + \kappa \times Rnd\left[\frac{2}{\sqrt{2\kappa}}\right]
\]

(11)

where \( Rnd[\sigma] \) is a random number generator for a gaussian distribution with standard deviation \( \sigma \). Typical for our setup is \( a_{\text{noise}} \approx 1.5 \times 10^{-3} \) and \( \text{const} \approx 1 \). The simulated signal in the time-domain is the sum of two exponentially decaying fields (Lorentzian bands), with the large band slightly smaller than the noise:

\[
\text{sig}(t[i]) = 10^{-3} \times \theta(t[i]) \left( \cos(\omega_1 t[i])e^{-t[i]/\tau_1} + 0.1 \cos(\omega_2 t[i])e^{-t[i]/\tau_2} \right)
\]

(12)
Here $\theta(t)$ is the unit step function. In Fig. 4 we have used $\tau_1 = 0.9$ ps, $\tau_2 = 1$ ps, $\omega_1/(2\pi c) = 2000 \text{ cm}^{-1}$, $\omega_2/(2\pi c) = 2100 \text{ cm}^{-1}$.

The time points $t[i]$ result from the simulated monotonous motor motion with random position errors. Signals calculated at these exact time points that lie within one HeNe time bin are averaged. Similar to the real experiment a binned interferogram of a gaussian pulse with the same phase as the signal is computed at the simulated time points and used to compute the phase for the Fourier transform of the data. In the simulations 'with chopper' we set $\text{sig}(t[i]) = 0$ for all even $i$ and divide by these (bin averaged) data points before Fourier transformation.

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20. J. Bredenbeck, J. Helbing, and P. Hamm, “Transient 2D-IR spectroscopy exploring


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Fig. 1. (Color online) Schematic view of a Fourier transform 2D-experiment in a photon echo geometry (left) and a pump probe geometry (right). In the echo geometry, so-called 're-phasing' and 'non re-phasing' signals are emitted in different directions. They are recorded by the same detector after inverting the time order of pulses (1) and (2) and must be added to obtain purely absorptive 2D-spectra. In the pump-probe geometry, pulses (1) and (2) are collinear and the sum of 'phasing' and 'non re-phasing' signals is measured directly.

Fig. 2. A: (Color online) Schematic representation of the setup. B: Beam path of the mid-IR light in the interferometer. A pyroelectric detector records pump pulse interferograms during every coherence time scan. C: Beam path for the HeNe laser propagating 2 cm above the mid-IR beam with separate beamsplitters BS1’ and BS2’ and static mirrors M3’ and M4’ for independent alignment. Interference between a circular polarized beam (λ/4 plate in the static interferometer arm) and a linear polarized beam gives rise to two orthogonally polarized signals with a relative 90 phase shift used for quadrature fringe counting. Mid-IR beamsplitters BS1 and BS2 may also be replaced by polarizers for measurements with perpendicular polarized pump pulses.

Fig. 3. (Color online) Phase determination A: Central section of the pump pulse interferogram recorded by the pyroelectric detector (circles). Open squares show the slope of the spectral phase near the band center after Fourier transform of the interferogram starting at different time bins \( k_0 \) (scale on left axis). B: Spectrum \( |A(\omega_1)| \) of the pump pulses (solid black line) and flat spectral phase \( \phi_K(\omega_1) \) (blue line) obtained after Fourier transform of the interferogram with \( k_0 = K = 106 \). Dotted lines show \( \phi_{k_0}(\omega_1) \) for \( k_0 = 99 \) and \( k_0 = 113 \). The black dashed line in B indicates the weak intensity scaling caused by averaging data over one HeNe laser period.

Fig. 4. (Color online) Effect of interferometer scan speed and chopping on signal to noise, illustrated by simulated Fourier spectra of two weak absorbers at 2000 cm\(^{-1}\) and 2100 cm\(^{-1}\) (intensity ratio 10:1). A and B: slow \( t_1 \) motor motion (0.06 mm/sec). C and D: fast \( t_1 \) motor motion (1.25 mm/sec). Blue (B and D) and red (A and C) lines represent Fourier transformed data with and without chopping, respectively. The insets in each graph show the simulated time domain data. The smooth lines in C indicate the analytic results.
Fig. 5. (Color online) Absorptive 2D spectra at of the Osmium carbonyl complex Os(dcbpy)I$_2$(CO)$_2$, attached to the porous surface of a nanoporous TiO$_2$ film. Two sets of diagonal and cross peaks originate from two different binding configurations [33]. ($t_1$-Fourier transform of the array detector signal with the phase factor $\phi_K$ automatically determined from the pump pulse interferogram, waiting time $t_2 = 1.5$ ps). A: data recorded without delay modulation. B: same sample spot but with $t_2$ delay modulated at $f_{rep}/4$ between $t_2 \pm \pi/\omega_0$ to suppress scatter to second order. C: Same data as in B after correction for the pump pulse spectrum.

Fig. 6. (Color online) A: amplitude of the residual scattering signal $\cos^n(\pi \omega_3/\omega_0)$ (in % of the original) after summing over two (black solid line, $n = 1$), three (red dashed line, $n = 2$) or four (green dotted line, $n = 3$) population delays in steps of $\pi/\omega_0$. B: Fast population time modulation, producing the correct amplitude and multiplicity of delays. Black solid: modulation amplitude $\pi/(2\omega_0)$, $f_{rep}/2$, red dashed: modulation amplitude $\pi/(2\omega_0)$, $f_{rep}/4$, green dotted: two modulators, amplitude ratio $(1 + \sqrt{2}) : 1$, frequencies $f_{rep}/8$ and $3f_{rep}/8$, relative phase shift $\pi/4$. 

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