Coherent femtosecond multidimensional probes of molecular vibrations

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Femtosecond visible and IR analogues of multiple-pulse NMR techniques provide snapshot probes of molecular structure and vibrational motions, interactions, and relaxation processes (1). The work of Larsen *et al.* (2) in a recent issue of PNAS makes a novel application of 2D IR spectroscopy to a rotaxane system whose mechanically interlocked architecture is often used in nanoscale molecular machines to provide large-amplitude controllable, reversible mechanical motion. Intermolecular noncovalent (e.g. hydrogen) bonding interactions provide multiple bonding sites between the macrocycle and thread, with the hysteretic character necessary for the operation of bistable switching devices in many applications, including nanocomputing and molecular electronics (3). The study reports a weak 3-cm^{-1} coupling between the ≈1,600-cm^{-1} carbonyl stretching modes of the thread and macrocycle that is very difficult to measure in any other way. This coupling, combined with cross-peak anistropy, allowed the extraction of the distance and angle of the two interlocked groups. Similar modes (the amide I vibrations) have been widely used in earlier studies of peptides and proteins (4–7). An exciting potential application of this technique to the real-time probing of molecular devices should be possible by combining it with a fast triggering (8).

Virtually all of the important developments in the field of nonlinear laser spectroscopy have followed the footsteps of NMR work done 20–30 years earlier. The celebrated work of Feynman, Vernon, and Hellwarth (9) had established the equivalence of spin 1/2 with an optically driven two-level system; coherent transients observed optically could then be associated with their NMR analogues. The spin-echo discovered by E. Hahn (24), a remarkable example of interference and time reversal, was followed by the photon echo observed in the nanosecond, picosecond, and eventually in the femtosecond regimes (10). These are only a few examples of NMR techniques that have been extended to optics. A new era began in the 1970s with the introduction of multidimensional NMR techniques by Richard Ernst (see ref. 25). The response of a system of coupled spins to a series of up to a few hundred pulses, when properly processed, gives extremely valuable information about complex molecular structure and dynamics (11). These techniques have now been extended to study molecular vibrations by using IR and visible pulses (12).

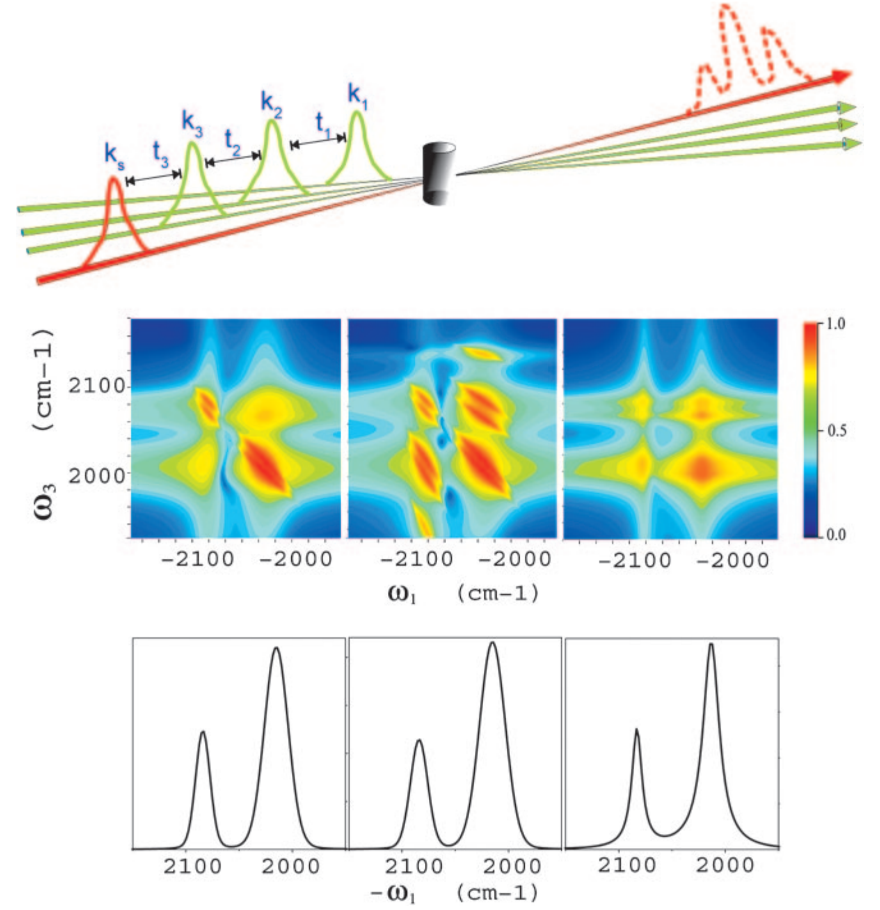

Fig. 1. Multiple pulse sequence and 2D IR correlation plots of coupled vibrations. (*Top*) Pulse configuration for a heterodyne four-wave mixing experiment. Signals are recorded vs. the three time delays and displayed as 2D correlation plots involving two of the time delays, holding the third fixed. (*Middle*) 2D photon echo spectra of two coupled vibrations in the direction $\mathbf{k}_s = -\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3$. ω_1 and ω_3 are the Fourier conjugate variables to t_1 and t_3. (*Left*) The frequency fluctuations of the two modes are slow and anticorrelated. (*Center*) Slow and correlated. (*Right*) Fast and anticorrelated. (Adapted from ref. 23.) (*Bottom*) Linear absorptions for the three models, plotted as a function of $-\omega_1$.

Spins are elementary quantum systems whose Hamiltonian depends on a few universal parameters. Vibrational and electronic motions are far more complex than spins and require new concepts and tools for designing of pulse sequences and extracting the desired information. Inversion algorithms (13) that could yield the interchromophore couplings and ultimately the distribution of structures directly from the signals may be used to produce real-time movies of dynamical events.

Optical four-wave mixing (Fig. 1) is the generic analogue of multidimensional NMR. Three pulses with wavevectors $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$ interact with the sample to generate a signal in one of the directions $\mathbf{k}_s = \pm\mathbf{k}_1 \pm \mathbf{k}_2 \pm \mathbf{k}_3$, which is then detected by mixing it with a fourth (heterodyne) pulse.

See companion article on page 13378 in issue 38 of volume 102.

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www.pnas.org/cgi/doi/10.1073/pnas.0506874102

This high directionality of the signal is characteristic to a coherent phase-sensitive process: the electric fields generated by different molecules in the sample add up in-phase only in these specific phase-matching directions and cancel otherwise. Recent advances in pulse-shaping technology allow us to vary the envelopes, polarization directions, durations, and time intervals, tune the frequencies, and even control the phases of optical pulses (14). By scanning these various parameters it is possible to custom-design a multiple-pulse technique for a specific application (as is routinely done in NMR). Displaying the signal by varying *n* parameters results in *n* dimensional correlation plots, which form the basis of *nD* spectroscopies. In an ideal time-domain experiment we control the intervals t_j between ≈50-fs pulses (Fig. 1). Frequency-domain techniques use long, temporally overlapping pulses (15), the time ordering of interactions with the various pulses is not enforced, and the control parameters are the frequencies. Spreading the spectroscopic information in more than one dimension helps resolve congested spectra, selectively eliminates certain static broadening mechanisms, and provides ultrafast structural and dynamical information unavailable from 1D measurements. Even when the 1D spectra are well resolved, 2D spectra can provide valuable fine details (e.g., couplings among chromophores).

Linear absorption provides a 1D projection of molecular interactions onto a single-frequency (or time) axis. Usually, many different microscopic models are consistent with the two-point correlation functions derived from conventional linear spectroscopy. In contrast, the molecular response to sequences of pulses provides a multidimensional view of their structure; correlation plots of dynamical events taking place during controlled evolution periods can be interpreted in terms of multipoint correlation functions that carry considerably more information than linear spectroscopy. This information can help distinguish between possible models whose 1D responses are virtually identical (1). Coupled vibrational modes show up as new resonances at combinations of single-mode resonant frequencies. These cross peaks, their intensities, and profiles give direct zero-background signatures of molecular structure (distances between chromophores) and dynamics (the spectral density of the chromophores' local environment). This is illustrated in the simulated photon echo $-\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3$ signals for a model of two coupled vibrations shown in Fig. 1. Fig. 1 represents different frequency fluctuation time scales and degrees of correlations of these fluctuations. The 2D lineshapes and cross peaks are very sensitive to these details. The linear absorption spectra of these three models have two peaks and are very similar.

The common thread of mulidimensional NMR and optical techniques is the coherent excitation of a collection of coupled chromophores (spins or localized vibrations). The multiple excitations of the various chromophores interact in a way that depends on molecular geometry and fluctuations, thus providing specific spectroscopic signatures through multiple quantum coherences.

Larsen *et al.* (2) used the pump-probe technique (16), which is the simplest member of the four-wave mixing family. Even though it uses only two pulses, it can be viewed as a four-pulse measurement whereby the system interacts twice with the pump and twice with the probe, and the signal is generated in the probe direction $\mathbf{k}_s = \mathbf{k}_1 - \mathbf{k}_1 + \mathbf{k}_2$. The control parameters are the frequencies ω_1 and ω_2 rather than the time delays. In that sense this measurement is a frequency-domain technique. Other multiple-pulse techniques may be used to provide successively high levels of information (17, 18).

Coherent nonlinear signals depend on delicate interferences among the possible sequences of population and coherence periods, which is the primary reason for their high sensitivity to fine structural and dynamical details. By manipulating and controlling interferences one can eliminate certain peaks, highlight desired features, and design pulse sequences for chiral structures (19, 20). One dramatic interference effect is that for harmonic vibrations whose dipole is proportional to the coordinates, the positive and negative contributions overlap and interfere destructively, and the nonlinear signal vanishes; the response is strictly linear (12). Cross peaks are associated with a different type of interference that closely resembles the double-slit experiment. The signal of two coupled vibrations A and B is not equal to the sum of their nonlinear responses; new pathways coming from the interaction of some of the laser pulses with A and others with B are responsible for the nonadditivity of the signal and give rise to the cross peaks.

Much of the activity in this field focuses on the IR response of molecular vibrations. However, the same ideas apply as well to electronic excitations of chromophore aggregates by visible pulses (21), as has been demonstrated recently for photosynthetic antenna complexes (22). Multidimensional signals provide unique probes for the excitation coherence size and the degree of cooperativity among chromophores, determined by the interplay of intermolecular interactions and dephasing effects caused by coupling to the environment.

This work was supported by National Institutes of Health Grant GM59230-05 and National Science Foundation Grant CHE-0446555.

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