Coherent two-dimensional terahertz-terahertz-Raman spectroscopy

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We present 2D terahertz-terahertz-Raman (2D TTR) spectroscopy, the first technique, to our knowledge, to interrogate a liquid with multiple pulses of terahertz (THz) light. This hybrid approach isolates nonlinear signatures in isotropic media, and is sensitive to the coupling and anharmonicity of thermally activated THz modes that play a central role in liquid-phase chemistry. Specifically, by varying the timing between two intense THz pulses, we control the orientational alignment of molecules in a liquid, and nonlinearly excite vibrational coherences. A comparison of experimental and simulated 2D TTR spectra of bromoform \((\text{CHBr}_3)\), carbon tetrachloride \((\text{CCl}_4)\), and dibromochloromethane \((\text{CBr}_2\text{Cl}_2)\) shows previously unobserved off-diagonal anharmonic coupling between thermally populated vibrational modes.

Results and Discussion

The 2D TTR experiment \((14–16)\) uses two intense carrier-envelope-phase \((\text{CEP})\) stable THz pump pulses followed by a weak 40-fs near-infrared \((\text{NIR})\) probe pulse. By adjusting the delay \(t_1\) between THz pulses, we control the phase of the THz radiation at the sample while maintaining a constant power. The heterodyne-detected transient birefringence is measured along the \(t_2\) axis with the NIR probe pulse from the same laser system. By Fourier transforming over the \(t_1\) and \(t_2\) times, one can generate 2D plots in the frequency domain. In an isotropic medium, such as a liquid, the lowest-order contribution to the measured nonlinear polarization is given by \((15, 19)\)

\[
P^{(3)}(t) = \int \int dt_1 dt_2 R^{(3)}(t_1, t_2) \tilde{E}_B(t - t_2) \tilde{E}_A(t - t_1 - t_2) \tilde{E}_{\text{nr}}(t),
\]

where \(R^{(3)}(t_1, t_2)\) is the third-order response function of the liquid, \(\tilde{E}_A(t - t_1 - t_2)\) and \(\tilde{E}_B(t - t_2)\) are the two THz pulses, and \(\tilde{E}_{\text{nr}}(t)\) is the NIR probe pulse. Weaker single-pulse third-order responses are removed by differential chopping \((\text{SI Appendix, Experimental Setup})\).

Significance

The thermally populated motions of liquids, including hydrogen bonds, low-energy bending vibrations, conformational torsions, and hindered rotations, are resonant in the terahertz region of the spectrum. These motions regulate solvation, macroscopic structure, and vibrational energy flow in liquid-phase chemistry. By exciting terahertz motions nonlinearly with multiple pulses of terahertz light, we can measure their anharmonic coupling and distribution of chemical environments. We can also begin to control their quantum coherence and population, a critical step forward in the control of liquid-phase chemistry with light.
Representative time domain 2D TTR signals. (A) The 2D time domain response of liquid bromoform. (B) Cutting the response in A beyond $t_2 = 1\,\text{ps}$ and detrending fits isolates the vibrational coherences.

We illustrate the principal components of a 2D TTR response function with the birefringent signal from liquid bromoform at 295 K (Figs. 1B, Left and 24). For the $t_1 = 0\,\text{fs}$ trace (Fig. 1B, Left, black line), the electronic response is visible as a sharp peak near $t_2 = 0\,\text{ps}$, which follows the E-field$^2$ (including phase) of the THz radiation (15). An exponential decay extending to $t_2 = 2\,\text{ps}$ results from the rotational diffusion of the molecules in the liquid as they reorient after aligning with the THz field (15). Nonlinear vibrational coherences from the excitation of the v6 mode are visible as a damped oscillation out to $t_2 = 4\,\text{ps}$ (16). As $t_1$ is shifted to 150 fs (red line), the transient birefringence is attenuated, whereas, at 250 fs (blue line), the response becomes negative. A full 2D scan of this $t_1$-dependent control is shown in Fig. 2A.

To understand the observed birefringence control, we return to the 2D TTR pulse sequence (Fig. L4). The polarizations of the THz pump pulses are orthogonal (shown in the black circles), and CEP is stable. By changing the phase offset ($\Delta\phi$) between the pulses, or $t_1$, we change the polarization of the total THz field ($E_{\text{tot}}$) when the pulses are overlapped in time (Fig. 1C). At $t_1 = 0\,\text{fs}$, $\Delta\phi = 0$, and $E_{\text{tot}}$ is oriented at +45 degrees with respect to the probe, whereas, at $t_1 = 250\,\text{fs}$, $\Delta\phi = \pi$, and $E_{\text{tot}}$ is oriented at +135 degrees with respect to the probe.

The electronic and nuclear alignment of the molecules follows the polarization of the THz radiation (15, 16). Thus, we posit that the change in the measured birefringence as a function of $t_1$ is due to angular control of the molecular alignment induced by the THz polarization (Fig. 1C). A simple orientational model of this behavior using the measured THz electric fields is shown in Fig. 1B, Right; it is an extension of the model used in our previous work (ref. 16 and SI Appendix, Orientational Model). The orientational model correctly predicts the sign changes and zero crossings of the birefringence, although it does not account for the nonlinear vibrational coherences. Thus, by varying the phase of the THz polarization at the sample, one can control the orientation of molecules in a liquid.

We now consider the damped oscillation shown in Figs. 1B, Left and 24. This component is due to the excitation of intramolecular vibrational coherences, and it provides information on the coupling and anharmonicity of vibrations in the liquid. It is best visualized with a 2D Fourier transform along the $t_1$ and $t_2$ axes starting at $t_2 = 1\,\text{ps}$, after detrending the orientational response with a single exponential fit for each $t_1$ scan (Fig. 2B).

The origins of the 2D TTR signatures can be derived using third-order perturbation theory on a three-level system, yielding 24 rephasing and nonrephasing Liouville pathways (SI Appendix, Perturbative Density Matrix Derivation). With phase-sensitive heterodyne detection, rephasing and nonrephasing Liouville pathways are differentiated in a 2D Fourier transform. Signals in the first quadrant ($f_1 = \pm, f_2 = \pm$) are nonrephasing, whereas signals in the second quadrant ($f_1 = \pm, f_2 = \mp$) arise from rephasing pathways (8, 19). The bandwidth (0.5–4 THz) of the THz pulses restricts the experiment to eight of the 24 pathways, all nonrephasing, two of which...
are shown in Fig. 3A. The sum of the eight pathways yields a response function \( R^{(3)}(t_1, t_2) \) given by

\[
R^{(3)}(t_1, t_2) \propto \mu_{ab}^2 H_{\text{IR}} \rho_{2}(\mu_{ab} e^{-i\omega_{ac}t_1} e^{-i\omega_{bc}t_2} - \mu_{bc} e^{-i\omega_{ab}t_1} e^{-i\omega_{ac}t_2}) + c.c.
\]

Here dipole and polarizability couplings are labeled as \( \mu_{xy} \) and \( \Pi_{xy} \), and the equilibrium population differences between states \( y \) and \( x \) as \( p_{yx} \) for the generalized three-level system. Thus, each peak in a 2D THz-THz-Raman spectrum results from a closed loop between three molecular eigenstates, hereafter denoted \(|a\rangle, |b\rangle, \) and \(|c\rangle\). Coherences are initiated by THz pump \( B \) and seen on the \( t_1 \) time or \( t_2 \) frequency axis. THz pump \( B \) moves these coherences to a new eigenstate, analogous to a coherence transfer pulse in 2D NMR. The loop is closed with a \(|c\rangle \rightarrow |a\rangle \) or \(|a\rangle \rightarrow |c\rangle \) Raman transition on the \( t_2 \) time, or \( t_2 \) frequency, axis. Similar to 2D Raman and 2D Raman-THz spectroscopy, every closed loop contains one or more transitions forbidden in the harmonic approximation, allowing us to directly measure the molecular anharmonicity (11, 20).

In Fig. 4, we demonstrate the capabilities of 2D TTR in measuring vibrational anharmonicities with the spectra of bromofom (CHBr\(_3\), 295 K), carbon tetrachloride (CCl\(_4\), 295 K), and dibromochloromethane (CBr\(_2\)Cl\(_2\), 313 K). For all three liquids, we observe peaks on the \( f_2 \) Raman axis that match the known lowest-energy intramolecular vibrations: \( \nu_6 \) in CHBr\(_3\) [SI Appendix, Reduced Density Matrix (RDM) Simulation] \( v_2 \) in CCl\(_4\) (21, 22), and \( \nu_4 \) and \( \nu_5 \) for CBr\(_2\)Cl\(_2\) (23). Returning to the closed-loop picture, the \( |c\rangle \rightarrow |a\rangle \) Raman transition is clearly assigned to changes of one quantum in each of these low-energy modes. The remaining mystery is the identity of the intermediate state \(|b\rangle \) in the closed loop, which can be examined by examining the \( f_1 \) positions of the peaks.

At \( \sim 300 \) K (\( k_B T \) = 6.2 THz), there is significant population in the low-energy vibrational and bath states of these liquids. Using linear Raman and THz spectra and Eq. 2, we observe the precise peak positions for coupling to different \(|b\rangle \) states for CHBr\(_3\), we observe a doublet \( f_2 \) peak that is consistent with anharmonic coupling between \( \nu_6 \) and \( \nu_3 \), but not with anharmonic coupling of \( \nu_6 \) to bath modes (Figs. 3B and 4A). CCl\(_4\) exhibits a similar doublet on the \( f_1 \) axis that matches a \( \nu_2 \rightarrow \nu_4 \) coupling (Figs. 3C and 4B). Simulated spectra from a reduced density matrix (RDM) method [SI Appendix, Reduced Density Matrix (RDM) Simulation] show good agreement with the experimental results (Fig. 4A and B, Right).

The thermally populated vibrational manifolds of CBr\(_2\)Cl\(_2\) (Fig. 5) are more complicated than those of CCl\(_4\) and CHBr\(_3\), which leads to further possibilities for vibrational coupling. However, a simple RDM simulation with eigenstates from the linear Raman spectrum and weak anharmonic \( \nu_4 \rightarrow \nu_7 \) and \( \nu_5 \rightarrow \nu_7 \) coupling reproduces all of the observed peaks (Fig. 4C and SI Appendix, Analysis of Experimental and RDM Simulated Spectra), and gives us insight into the relative coupling strengths in this liquid. Specifically, we see that the two lowest-energy vibrational modes are more strongly coupled to \( \nu_7 \) than to \( \nu_3 \) and \( \nu_9 \).

**Summary**

In summary, we have demonstrated, to our knowledge, the first 2D spectroscopy of liquids that is nonlinear in the THz field. With two time-delayed THz pulses and an NIR probe pulse, we can control the orientational alignment of molecules in a liquid and generate 2D THz-THz-Raman spectra that are sensitive to anharmonic vibrational coupling. We measure significant coupling in the lowest-frequency intramolecular modes of liquid CHBr\(_3\), CCl\(_4\), and CBr\(_2\)Cl\(_2\).

The off-diagonal peaks measured in the 2D TTR spectra provide information that is not present in a 1D linear spectrum. Specifically, the linear THz peaks of a liquid reveal the energies of its molecular eigenstates, whereas the off-diagonal 2D TTR peaks show the coupling between these eigenstates. The features measured here are, by definition, cross peaks, because they correlate a frequency on the pump axis to a different frequency on the probe axis. This allows us, for example, to show that, in CBr\(_2\)Cl\(_2\), \( \nu_4 \) and \( \nu_5 \) are most strongly coupled to \( \nu_7 \)—information unobtainable in a linear spectrum. These off-diagonal peaks also allow us to determine individual components of an inhomogeneously broadened feature in the linear spectrum. This is the case in CHBr\(_3\) and CCl\(_4\), which show an inhomogeneously broadened absorption from 0.1 THz to 3.5 THz (SI Appendix, Reduced Density Matrix (RDM) Simulation and refs. 21 and 22). It is impossible to resolve the components of these features with a linear measurement, as the broadening is intrinsic to the liquids. The 2D TTR spectra, however, reveal several distinct components due to difference band transitions between intramolecular modes.
Although limited in these first experiments, we expect 2D TTR sensitivity improvements of >100× using existing technologies (24, 25). Such improvements should enable the measurement of photon echo (rephasing) signals and permit studies of intermolecular vibrations in isotropic molecular solids and hydrogen-bonded liquids. The importance of THz-active motions in biochemistry is well documented (26), and 2D TTR studies could ultimately provide new insights on processes such as protein folding and DNA internal conversion.

**Materials and Methods**

**Experiment.** We generate 3.6-mJ pulses of 38 fs duration from an 800-nm Coherent Legend Elite USP Ti:Sa regenerative amplifier. The pulses from the amplifier are sent into an optical parametric amplifier (Light Conversion Ltd.) and downconverted to 1,450 nm (signal, 500 μJ) and 1,780 nm (idler, 330 μJ). The signal is routed through a delay line (t₁) and used to drive a 3-mm aperture 4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate (DSTMS) THz generation crystal (Rainbow Photonics). The idler is sent to a second DSTMS crystal. The two THz pulses are combined on a knife edge mirror, magnified by 7.5×, and focused on the sample with a 2-inch EFL 90-degree off-axis parabolic mirror. The peak field strengths of both pulses are ~300 kV/cm. Liquids are held in a 1-mm-path-length Suprasil quartz cuvette. The transient birefringence in the sample is probed with a small portion of the 800-nm light from the amplifier, and sent down a second delay line (t₂). As described in our previous work, we heterodyne detect the transient birefringence using a 10⁻⁵:1 polarizer, a λ/4 plate, a Wollaston prism, and a pair of silicon photodiodes (16). The signal is isolated with differential chopping of the signal and idler beams and detected with a lock-in amplifier (SI Appendix, Experimental Setup).

**Orientational Model.** The electronic and orientational components of the measured signal are due to a change in the sample birefringence, or a difference in refractive index along the vertical and horizontal directions. The birefringent signal is predicted using the measured THz fields (15, 16). More details of the model are given in SI Appendix, Orientational Model.

**RDM Simulation.** An RDM approach (19, 27) is used to qualitatively simulate the 2D TTR spectra. The time evolution of the RDM ρ is given by the Liouville–Von Neumann equation

![Fig. 4. Experimental (Left) and RDM simulated (Right) 2D TTR spectra of (A) CHBr₃, (B) CCl₄, and (C) CBr₂Cl₂. The f₁ axis corresponds to the THz pump, and the f₂ axis corresponds to the optical Raman probe.](image-url)
where $H$ is the matrix representation of the Hamilton operator of the system under consideration. In this work, the time evolution is numerically calculated using a second-order differencing technique (28),

$$p(t + \Delta t) = p(t) - \frac{i}{\hbar} [H, p](t) 2\Delta t - 2i\Delta t,$$

where $\Gamma_{ij} = (1 - \delta_{ij})/\tau_{ij}$ defines the off-diagonal decay that is needed to phenomenologically incorporate dephasing caused by the surrounding bath.


Fig. 5. The vibrational energy levels of CBr$_2$Cl$_2$. Observed THz excitations are shown as black arrows, and those for Raman excitations are in red.