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Letter

Quantum Interferometric Pathway Selectivity in Difference-Frequency-Generation Spectroscopy

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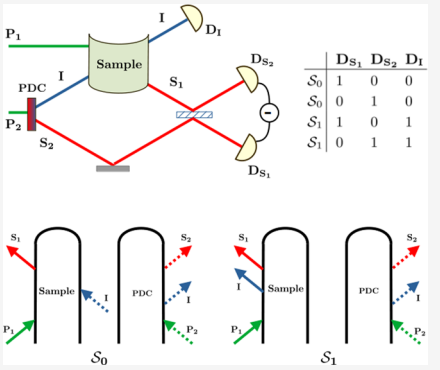
ABSTRACT: Even-order spectroscopies such as sum-frequency generation (SFG) and difference-frequency generation (DFG) can serve as direct probes of molecular chirality. Such signals are usually given by the sum of several interaction pathways that carry different information about matter. Here we focus on DFG, involving impulsive optical−optical−IR interactions, where the last IR pulse probes vibrational transitions in the ground or excited electronic state manifolds, depending on the interaction pathway. Spectroscopy with classical light can use phase matching to select the two pathways. In this theoretical study, we propose a novel quantum interferometric protocol that uses entangled photons to isolate individual pathways. This additional selectivity originates from engineering the state of light using a Zou−Wang−Mandel interferometer combined with coincidence detection.



By symmetry, second-order spectroscopic signals $\chi^{(2)}$ vanish in centrosymmetric media.[1−5] As such, they provide sensitive probes of interfaces and of ensembles of randomly oriented chiral molecules,[6−9] in the gas or liquid phase. Sum- and difference-frequency generation (SFG and DFG, respectively) are widely used as chiral-sensitive signals. Time-domain SFG with an infrared pump and an optical probe is commonly used to probe vibrational frequencies and dephasing rates. Controlling the pulse time ordering and the signal direction (phase matching) can generally select groups of relevant pathways but not a single pathway.[10,11] DFG, for example, has two pathways (shown in Figure 3),[12,13] which represent different vibrational transitions in the ground or the excited states. The ability to select a single pathway could simplify the interpretation of signals.

Quantum light provides additional control knobs compared to classical light.[14−18] Entangled photons have been shown to allow better joint spectral-temporal resolution not subjected to the Fourier uncertainty.[19] They further allow carrying out nonlinear spectroscopies at low intensities, making them suitable for studying fragile biological samples.[20−25] Several multidimensional spectroscopy techniques based on entangled photons have been proposed.[26−28]

In this theoretical study, we propose a novel interferometer setup with quantum light, see Figure 1, which can select a single pathway (rather than two) in DFG. This allows better resolution of vibrational transitions in the ground and excited electronic states. Multiphoton interferometers and coincidence counting techniques are commonly used in quantum optics[29−31] and have been proposed to improve the spectral and temporal resolutions in spectroscopy.[32−37]

Recently we have demonstrated pathway selectivity in third order double-quantum-coherence signals.[38] Pathway selectivity in a Raman process without interferometry was discussed in ref. 39. Here we show how to select pathways in DFG using photon-number-resolved detectors in an interferometeric setup.

The proposed setup, depicted in Figure 1, is inspired by the Zou−Wang−Mandel interferometer[40−42] which uses two nonlinear crystals. Recently the Zou−Wang−Mandel interferometer was used for performing imaging[43] and spectroscopy[44,45] with undetected photons.

A single-photon pulse propagating along the optical path $\mathbf{P}$ with polarization ($\boldsymbol{\epsilon}_p$) is split by a beam splitter, into a superposition of two single photon pulses, $\mathbf{P}_1$ and $\mathbf{P}_2$, with the same polarization and a controlled time delay $\delta\tau_p$. $\mathbf{P}_2$ is further split using a nonlinear crystal by undergoing a spontaneous parametric down conversion process, into an entangled photon pair $\mathbf{S}_2$ and $\mathbf{I}$, with respective polarizations $\boldsymbol{\epsilon}_s$ and $\boldsymbol{\epsilon}_i$ and a second controlled time delay $\delta\tau_{si}$. The state of light is then given by a superposition of a single photon pulse $\mathbf{P}_1$ and entangled single photon pulses $\mathbf{I}$ and $\mathbf{S}_2$,

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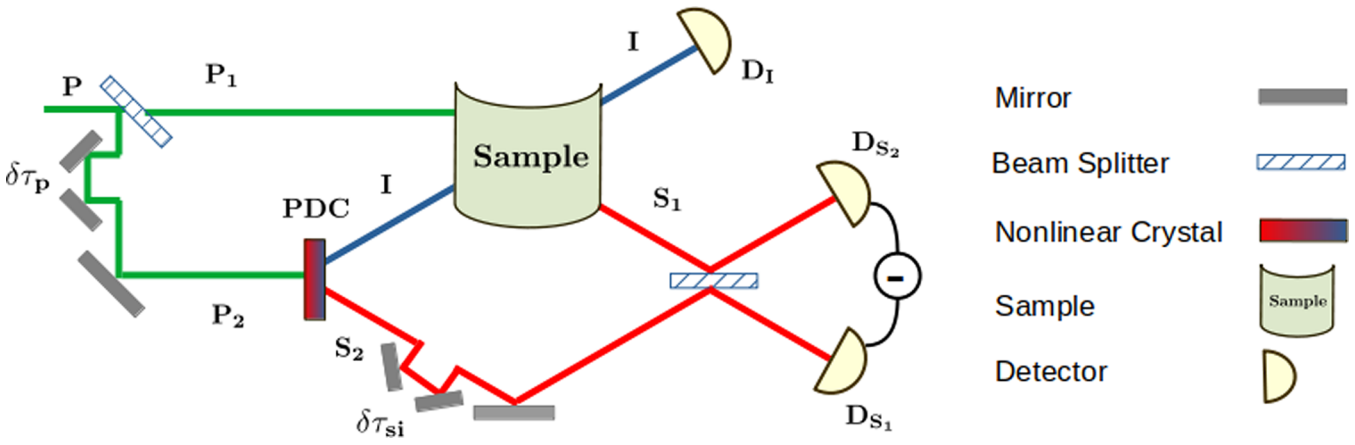

Figure 1. Proposed Zou−Wang−Mandel interferometer for selecting Liouville space pathways in ultrafast DFG spectroscopy. Engineered state of photons along with coincidence detection of photons at the three detectors provides a route for this selectivity.

$$|\Psi(-\infty)\rangle = \frac{1}{\sqrt{2}}[\int_{-\infty}^{+\infty} d\omega_p \phi(\omega_p) a^{\dagger}_{p_1\epsilon_p}(\omega_p) + \int_{-\infty}^{+\infty} d\omega_s d\omega_i \psi(\omega_s, \omega_i) e^{i\omega_s(\delta\tau_p+\delta\tau_{si})+i\omega_i\delta\tau_p} a^{\dagger}_{s_2\epsilon_s}(\omega_s) a^{\dagger}_{i\epsilon_i}(\omega_i)]|\varnothing\rangle \quad (1)$$

where $|\varnothing\rangle$ is the vacuum state of the electromagnetic field and $a_{\alpha\epsilon}(\omega)$ is the bosonic annihilation operator of a photon with frequency ω and polarization ϵ propagating along the optical path α. In the present application, pulses $\mathbf{P_1}$ and $\mathbf{I}$ are in the ultraviolet range and $\mathbf{S_2}$ is infrared. More details are given in the appendix.

Pulses $\mathbf{P_1}$ and $\mathbf{I}$ then interact with the sample to generate a third pulse $\mathbf{S_1}$ via a DFG process. This is ensured by (i) the phase matching condition at the **nonlinear crystal** (**PDC**), $\boldsymbol{k}_{S_2} = \boldsymbol{k}_{P_2} - \boldsymbol{k}_I$, and at the **Sample**, $\boldsymbol{k}_{S_1} = \boldsymbol{k}_{P_1} - \boldsymbol{k}_I$, together with selecting the signals along $\boldsymbol{k}_{S_2}$ and $\boldsymbol{k}_{S_1}$, ensures that the idlers direction is identical, $\boldsymbol{k}_I$, and (ii) pulses $\mathbf{P_1}$ and $\mathbf{I}$, which pass through the sample have a photon in one of them, but not in both (as can be seen from eq 1), and hence do not allow an SFG process.

Finally, a coincidence measurement which includes (i) photon number resolved detection of pulse $\mathbf{I}$ at the detector $\mathbf{D_I}$ and (ii) difference of intensities recorded at the detectors $\mathbf{D_{S_1}}$ and $\mathbf{D_{S_2}}$, which measures coherence (heterodyne) of photons in pulses $\mathbf{S_1}$ and $\mathbf{S_2}$, respectively, generated at the sample and crystal. Our signal is finally defined by $\langle I_{D_I}(n_i)(I_{D_{S1}} - I_{D_{S2}})\rangle$. This coincidence detection, as will be shown below, selectively isolates each Liouville space pathway in Figure 3, based on the photon number in pulse $\mathbf{I}$.

We consider a molecular model system, Figure 2, with two electronic states and their vibrational manifolds. The total matter and field Hamiltonian are given by

$$H = \underset{\text{system}}{H_s} + \underset{\text{field}}{H_f} + \underset{\text{system-field}}{H_{sf}} \quad (2)$$

$$H_s = \sum_{\sigma=g,e}\sum_{n\in\sigma} \hbar\omega_{\sigma_n}|\sigma_n\rangle\langle\sigma_n| \quad (3)$$

$$H_f = \sum_{\alpha\in\mathcal{I}}\sum_{\lambda}\int_{-\infty}^{+\infty} d\omega \hbar\omega a^{\dagger}_{\alpha\epsilon_\lambda}(\omega) a_{\alpha\epsilon_\lambda}(\omega) \quad (4)$$

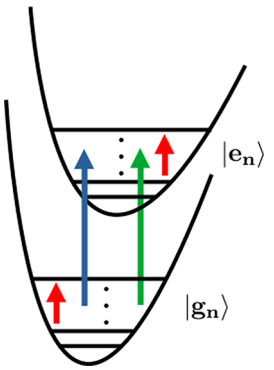

Figure 2. Energy level scheme for a molecular model system consisting of two electronic states (labeled as g and e) each having its own vibrational manifold (labeled by the subscripts g_n and e_n). Optical transitions are the intermanifold vibronic transitions and intramanifold vibrational transitions.

$$H_{sf} = \sum_{\alpha\in p_1,s_1,i} [\mathcal{E}^{\dagger}_{\alpha}\cdot\boldsymbol{V} + \boldsymbol{V}^{\dagger}\cdot\mathcal{E}_{\alpha}] \quad (5)$$

where $\mathcal{I} = p, p_1, p_2, s_1, s_2, i$ indicates a sum over all optical paths in the interferometer. $|\sigma_n\rangle$ denotes the n^{th} vibrational state in the σ = g, e manifold. The electric field operator is given by $\mathcal{E}_\alpha = ic_\alpha\sum_\lambda \epsilon_\lambda \int_{-\infty}^{+\infty} d\omega a_{\alpha\epsilon_\lambda}(\omega)$, with $c_\alpha = \sqrt{\frac{\hbar\bar{\omega}_\alpha}{4\pi\epsilon_0 cA}}$. A is the transverse area and $\bar{\omega}_\alpha$ is the central frequency of the pulse along path α. The transition dipole operator is given by

$$\boldsymbol{V} = \sum_{\sigma,\sigma'}\sum_{\substack{n\in\sigma,n'\in\sigma' \\ \omega_{\sigma_n}<\omega_{\sigma'_{n'}}}} \boldsymbol{\mu}_{\sigma_n\sigma'_{n'}}|\sigma_n\rangle\langle\sigma'_{n'}|$$

In the above, the light−matter interaction is given in the rotating-wave approximation.

The coincidence detection of n_i idler photons with heterodyne detection of $\mathbf{S_1}$ and $\mathbf{S_2}$, S_{n_i}, is, for $n_i = 0$

$$S_0 = \frac{1}{\pi c_{s1} c_{s2}}\text{Im}\int_{-\infty}^{+\infty} dt_s dt_i \left\langle \mathcal{T}\mathcal{E}^{\dagger}_{s_2R}(t_s)\cdot\mathcal{E}_{s_1L}(t_s) \left[\delta(t_i) - \frac{1}{2\pi c_i^2}\mathcal{E}^{\dagger}_{iR}(t_i)\cdot\mathcal{E}_{iL}(t_i)\right]\right\rangle \quad (6)$$

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and for $n_i = 1$

$$\mathcal{S}_1 = \frac{1}{2\pi^2 c_{s1} c_{s2} c_i^2} \mathrm{Im} \int_{-\infty}^{+\infty} \mathrm{d}t_s \mathrm{d}t_i \langle \mathcal{T} \mathcal{E}_{s_2 R}^{\dagger}(t_s) \cdot \mathcal{E}_{s_1 L}(t_s) \mathcal{E}_{iR}^{\dagger}(t_i) \cdot \mathcal{E}_{iL}(t_i) \rangle \tag{7}$$

where $O(t)$ is an interaction-picture operator. The subscripts L, R are superoperator indices representing the action of the operator on the left (ket) or right (bra). Furthermore, $\langle \mathcal{T} \cdots \rangle = \mathrm{Tr}[\mathcal{T} \cdots e^{-(i/\hbar)\int_{-\infty}^{\infty} \mathrm{d}t H_{sf-}(t)} \rho(-\infty)]$, $\rho(-\infty) = |g_1\rangle\langle g_1| \otimes |\Psi(-\infty)\rangle\langle\Psi(-\infty)|$ is the joint initial density matrix of the system and the field. Here $|g_1\rangle$ denotes the ground vibrational state of the ground electronic manifold of the system.

The motivation for the coincidence signals is as follows: When the signals are recorded, only two possible pathways of the light−matter interaction are possible, as represented by the loop diagrams in Figure 3. Figure 3 ($\mathcal{S}_0$) corresponds to a photon in pulse $\mathbf{P}_1$ and a photon in pulse $\mathbf{I}$ being absorbed by the system on the left (ket) and right (bra) side of the joint matter-field density matrix, followed by $\mathbf{S}_1$ photon emission. This results in no final photon in pulse $\mathbf{I}$ and a coherence between photons in pulses $\mathbf{S}_1$ and $\mathbf{S}_2$, which contributes to the signal $\mathcal{S}_0$. This leads to two possible photon count scenarios in the three detectors given in the first two columns of Table 1. Hence, $\mathcal{S}_0$, which measures coherence between $\mathbf{S}_1$ and $\mathbf{S}_2$ combined with zero photons in $\mathbf{I}$, selects Figure 3 ($\mathcal{S}_0$). For diagram Figure 3 ($\mathcal{S}_1$), a photon from pulse $\mathbf{P}_1$ is absorbed by the system on the left side, followed by sequential emission of photons along $\mathbf{I}$ and $\mathbf{S}_1$ on the left side. This results in a single photon in pulse $\mathbf{I}$ and coherence between photons in pulses $\mathbf{S}_1$ and $\mathbf{S}_2$, which contributes to the signal $\mathcal{S}_1$.

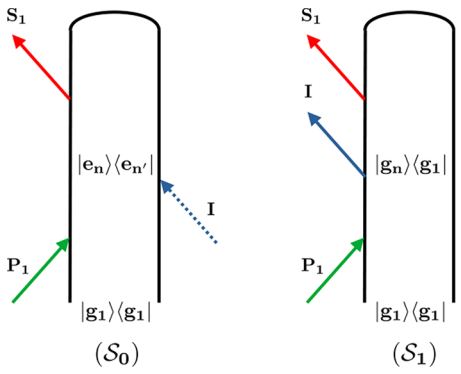

Figure 3. Loop diagrams contribute to the signals. The classical ultrafast DFG signal, $\mathcal{S}^{(c)}$, is given by the sum of both diagrams.

Table 1. Possible Photon Counts at the Detectors for Different Pathways Selected by the Interferometric Signals[a]

	$\mathbf{D}_{\mathbf{S}_1}$	$\mathbf{D}_{\mathbf{S}_2}$	$\mathbf{D}_{\mathbf{I}}$
$\mathcal{S}_0$	1	0	0
$\mathcal{S}_0$	0	1	0
$\mathcal{S}_1$	1	0	1
$\mathcal{S}_1$	0	1	1

[a]The final photon distribution of pulse $\mathbf{I}$, conditioned on a single photon in either of the pulses $\mathbf{S}_1$ or $\mathbf{S}_2$, distinguishes between different Liouville space pathways. Null/one photon count in pulse $\mathbf{I}$ selects Figure 3 ($\mathcal{S}_0/\mathcal{S}_1$).

This leads to two possible photon count scenarios at the three detectors given in the last two columns of Table 1. Hence, $\mathcal{S}_1$, which measures coherence between $\mathbf{S}_1$ and $\mathbf{S}_2$ in coincidence with a photon in $\mathbf{I}$, selects the loop diagram in Figure 3 ($\mathcal{S}_1$). Thus, the proposed coincidence signals can selectively measure the two loop diagrams in Figure 3. Both diagrams in Figure 3 satisfy the same phase-matching condition $\boldsymbol{k}_{\mathbf{S}_1} = \boldsymbol{k}_{\mathbf{P}_1} - \boldsymbol{k}_{\mathbf{I}}$ and hence cannot be separated by a classical DFG measurement which only measures $\mathbf{S}_1$. However, they differ in the final state of the $\mathbf{I}$ field, which is measured in the interferometric measurement. Measuring more than one (as opposed to a single field in a classical measurement) is the key for the pathway selectivity. More additional details are given in the Supporting Information.

Below we present expressions for these signals in terms of system and field multipoint correlation functions. Sum-over-states expressions for the signals are derived as well.

Expanding eqs 6 and 7 to third order in the light−matter coupling and using eq 1 gives

$$\mathcal{S}_0(\bar{\omega}_p, \delta\tau_{si}) = -\mathrm{Im}\left(-\frac{i}{\hbar}\right)^3 \sum_{l,m,n=x,y,z} \int_{-\infty}^{+\infty} \mathrm{d}t_1 \mathrm{d}t_2 \mathrm{d}t_3 \langle \mathcal{T} V_L^l(t_1) V_R^m(t_2) V_L^{n\dagger}(t_3) \rangle_s \langle \mathcal{T} \mathcal{E}_{s_2 L}^{l\dagger}(t_1) \mathcal{E}_{iR}^{m\dagger}(t_2) \mathcal{E}_{p_1 L}^{n}(t_3) \rangle_f \tag{8}$$

and

$$\mathcal{S}_1(\bar{\omega}_p, \delta\tau_{si}) = \mathrm{Im}\left(-\frac{i}{\hbar}\right)^3 \sum_{l,m,n=x,y,z} \int_{-\infty}^{+\infty} \mathrm{d}t_1 \mathrm{d}t_2 \mathrm{d}t_3 \langle \mathcal{T} V_L^l(t_1) V_L^m(t_2) V_L^{n\dagger}(t_3) \rangle_s \langle \mathcal{T} \mathcal{E}_{s_2 L}^{l\dagger}(t_1) \mathcal{E}_{iL}^{m\dagger}(t_2) \mathcal{E}_{p_1 L}^{n}(t_3) \rangle_f \tag{9}$$

The signals $\mathcal{S}_0$ and $\mathcal{S}_1$ depend on the following control parameters: the pulses central frequencies ($\bar{\omega}_{p_1/s_2/i}$), their widths, and the time delays ($\delta\tau_p$ and $\delta\tau_{si}$) between the pulses $\mathbf{P}_1$, $\mathbf{S}_2$, and $\mathbf{I}$. They also depend on the entanglement time of pulses $\mathbf{S}_2$ and $\mathbf{I}$. In the above equations and in the following, we only indicate explicit dependence on $\bar{\omega}_p$ and $\delta\tau_{si}$, which are scanned to obtain the spectral information on the system, while all the other parameters are held constant. We note that, due to the quantum nature of the electromagnetic field interacting with the sample, the above signals cannot be solely expressed in terms of the classical causal response function of matter.[46] Since the signals $\mathcal{S}_0$ and $\mathcal{S}_1$ are obtained using an engineered quantum state of light and a quantum interferometer, we refer to them as the quantum signals in the following.

$$\langle \mathcal{T} V_L^l(t_1) V_{L/R}^m(t_2) V_L^{n\dagger}(t_3) \rangle_s$$

and

$$\langle \mathcal{T} \mathcal{E}_{s_2 L}^{l\ \dagger}(t_1) \mathcal{E}_{iL/R}^{m\ \dagger}(t_2) \mathcal{E}_{p_1 L}^{n}(t_3) \rangle_f$$

are respectively the system and field multipoint correlation functions. The system and field correlation functions are computed with their respective initial states $|g_1\rangle\langle g_1|$ and $|\Psi(-\infty)\rangle\langle\Psi(-\infty)|$, with $|\Psi(-\infty)\rangle$ given in eq 1. The system and field operators evolve according to their respective Hamiltonians given in eq 2.

These signals are represented by the loop diagrams in Figure 3. These loop diagrams are time ordered in loop time and not the real time.[47,48] Depending on the relative time ordering of left and right operators, each loop diagram represents one or more ladder diagrams that are completely time ordered. The loop diagram in Figure 3 ($\mathcal{S}_0$), contributing to $\mathcal{S}_0$, is represented by

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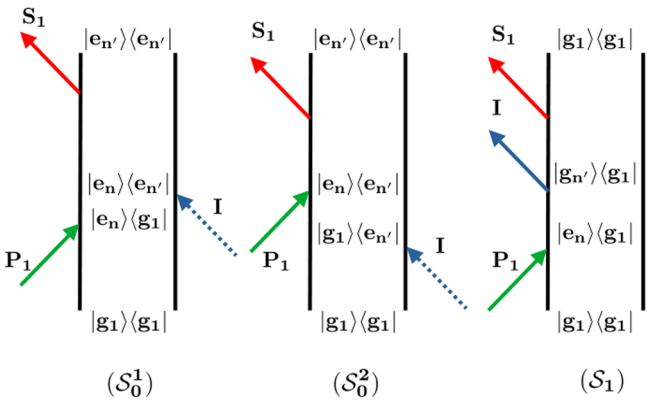

Figure 4. Ladder diagrams corresponding to the loop diagrams of Figure 3. Diagrams $(\mathcal{S}_0^1)$ and $(\mathcal{S}_0^2)$ contribute to $\mathcal{S}_0$, and diagram $(\mathcal{S}_1)$ contributes to $\mathcal{S}_1$. The classical ultrafast DFG signal is given by the sum of all diagrams.

the two ladder diagrams of Figures 4 $(\mathcal{S}_0^1)$ and 4 $(\mathcal{S}_0^2)$, whereas the loop diagram in Figure 3 $(\mathcal{S}_1)$, contributing to $\mathcal{S}_1$, is represented by a single ladder diagram in Figure 4 $(\mathcal{S}_1)$. We assumed that the entangled photons in pulses $\mathbf{S}_2$ and $\mathbf{I}$ are time ordered such that $\mathbf{I}$ comes first. Moreover, in Figure 4, we assumed that pulses $\mathbf{P}_1$ and $\mathbf{I}$ are resonant with interband transitions, whereas $\mathbf{S}_1$ is resonant with intraband transitions.

The two pathways shown in Figure 3, involving ground or excited state vibrational transitions,[12] can thus be sorted out, based on the number of detected photons in the idler pathway. The diagram in Figure 3 $(\mathcal{S}_0)$ describes the signal originating from excited state vibrational coherence, while Figure 3 $(\mathcal{S}_1)$ corresponds to ground state vibrational coherence. The present selectivity in probing these two pathways could find applications in probing excited states of chiral molecules in the bulk and at chiral interfaces.

For an ensemble of randomly oriented molecules, the bulk macroscopic signal can be obtained from the above single molecule signal by averaging over molecular orientations.[49] We note that the rotationally averaged signals vanish for achiral molecules and hence selectively probe chirality. The rotationally averaged quantum signals are finally given by,

$$\mathcal{S}_0(\bar{\omega}_p, \delta\tau_{si}) = -\frac{1}{3!}\mathrm{Im}\left(-\frac{i}{\hbar}\right)^3 \int_{-\infty}^{+\infty} \mathrm{d}t_1\mathrm{d}t_2\mathrm{d}t_3 \langle \mathcal{T}\boldsymbol{V}_L(t_1) \times \boldsymbol{V}_R(t_2)\cdot\boldsymbol{V}_L^{\dagger}(t_3)\rangle_s \langle \mathcal{T}\boldsymbol{\mathcal{E}}_{s_2L}^{\dagger}(t_1) \times \boldsymbol{\mathcal{E}}_{iR}^{\dagger}(t_2)\cdot\boldsymbol{\mathcal{E}}_{p_1L}(t_3)\rangle_f \tag{10}$$

and

$$\mathcal{S}_1(\bar{\omega}_p, \delta\tau_{si}) = \frac{1}{3!}\mathrm{Im}\left(-\frac{i}{\hbar}\right)^3 \int_{-\infty}^{+\infty} \mathrm{d}t_1\mathrm{d}t_2\mathrm{d}t_3 \langle \mathcal{T}\boldsymbol{V}_L(t_1) \times \boldsymbol{V}_L(t_2)\cdot\boldsymbol{V}_L^{\dagger}(t_3)\rangle_s \langle \mathcal{T}\boldsymbol{\mathcal{E}}_{s_2L}^{\dagger}(t_1) \times \boldsymbol{\mathcal{E}}_{iL}^{\dagger}(t_2)\cdot\boldsymbol{\mathcal{E}}_{p_1L}(t_3)\rangle_f \tag{11}$$

Equations 10 and 11 are the main results of this work. We compare them with the classical heterodyne detected DFG signal generated by three temporally separated classical pulses, $\tilde{\boldsymbol{E}}_s(t)$, $\tilde{\boldsymbol{E}}_i(t)$ and $\tilde{\boldsymbol{E}}_p(t)$,

$$\mathcal{S}^{(c)}(\bar{\omega}_p, \delta\tau_{si}) = \frac{2}{3!}\mathrm{Im}\left(-\frac{i}{\hbar}\right)^3 \int_{-\infty}^{+\infty} \mathrm{d}t_1\mathrm{d}t_2\mathrm{d}t_3 \tilde{\boldsymbol{E}}_s^*(t_1) \times \tilde{\boldsymbol{E}}_i^*(t_2)\cdot\tilde{\boldsymbol{E}}_p(t_3) [\langle \mathcal{T}\boldsymbol{V}_L(t_1) \times \boldsymbol{V}_L(t_2)\cdot\boldsymbol{V}_L^{\dagger}(t_3)\rangle_s - \langle \mathcal{T}\boldsymbol{V}_L(t_1) \times \boldsymbol{V}_R(t_2)\cdot\boldsymbol{V}_L^{\dagger}(t_3)\rangle_s] \tag{12}$$

Details of this classical signal are given in the Supporting Information.

By comparing the quantum signals (eqs 10 and 11) with the classical signal (eq 12), it is clear that the quantum signals can selectively probe each of the two contributions to the classical signal. As can be seen from Figure 4, the signals $\mathcal{S}_0$ and $\mathcal{S}_1$ probe excited state and ground state vibrational coherences, respectively. This separation is not possible with the classical signal.

For the state of light given in eq 1, the field correlation functions factorize as

$$\begin{aligned}&\langle \mathcal{T}\boldsymbol{\mathcal{E}}_{s_2L}^{\dagger}(t_1) \times \boldsymbol{\mathcal{E}}_{iL/R}^{\dagger}(t_2)\cdot\boldsymbol{\mathcal{E}}_{p_1L}(t_3)\rangle_f \\ &= \langle \Psi(-\infty)|\mathcal{T}\boldsymbol{\mathcal{E}}_{s_2}^{\dagger}(t_1) \times \boldsymbol{\mathcal{E}}_i^{\dagger}(t_2)|\varnothing\rangle\cdot\langle\varnothing|\boldsymbol{\mathcal{E}}_{p_1}(t_3)|\Psi(-\infty)\rangle \\ &= (2\pi i)^3 c_{s_2}c_{p_1}c_i\boldsymbol{\epsilon}_s^* \times \boldsymbol{\epsilon}_i^*\cdot\boldsymbol{\epsilon}_p\tilde{\psi}^*(t_1 - \delta\tau_{si} - \delta\tau_p, t_2 - \delta\tau_p)\tilde{\phi}(t_3)\end{aligned} \tag{13}$$

where the classical pulse and entangled pulses temporal amplitudes respectively are

$$\tilde{\phi}(t) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}\omega}{2\pi}\phi(\omega)\mathrm{e}^{-i\omega t}$$

and

$$\tilde{\psi}(t_1, t_2) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}\omega_1}{2\pi}\frac{\mathrm{d}\omega_2}{2\pi}\psi(\omega_1, \omega_2)\mathrm{e}^{-i\omega_1 t_1 - i\omega_2 t_2}$$

Hereafter, we assume the following frequency profiles for the classical pump pulse $(\phi(\omega_p))$ and the entangled photon pulses $(\psi(\omega_s, \omega_i))$ as

$$\begin{aligned}\phi(\omega_p) &= \sqrt{I_p}\sqrt{\frac{\sigma_p^2}{2\pi}}\, e^{-\sigma_p^2(\omega_p - \bar{\omega}_p)^2/2} \\ \psi(\omega_s, \omega_i) &= C\phi(\omega_s + \omega_i)\mathrm{sinc}\left(\frac{(\omega_s - \omega_i - \bar{\omega}_s + \bar{\omega}_i)}{4}T_e\right) e^{i[(\omega_s - \omega_i - \bar{\omega}_s + \bar{\omega}_i)/4]T_e}\end{aligned} \tag{14}$$

where the profile of the pulses $\mathbf{P}_1$ and $\mathbf{P}_2$ are identical, with the central frequency $\bar{\omega}_p$, temporal width σ_p, and intensity I_p. Central frequencies of $\mathbf{S}_2$ and $\mathbf{I}$ are respectively $\bar{\omega}_s$ and $\bar{\omega}_i = \bar{\omega}_p - \bar{\omega}_s$. The constant C contains the details of the nonlinear crystal used to generate entangled photons, and T_e is the entanglement time.

Note that the contribution from diagram in Figure 4 $(\mathcal{S}_0^2)$ to $\mathcal{S}_0$ can be suppressed for $\delta\tau_p \gg \sigma_p$, i.e., by reducing the temporal overlap of the pump pulse $\mathbf{P}_1$ and the idler pulse $\mathbf{I}$.

With this, the quantum signals become

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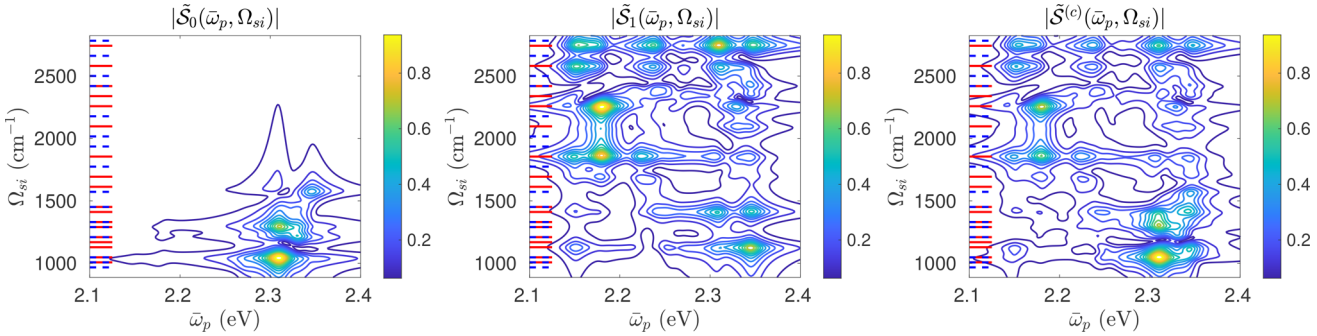

Figure 5. (Normalized) quantum signals, $|\tilde{S}_0|$ (eq 17 and diagram Figure 4 ($\mathcal{S}_0^1$)) and $|\tilde{S}_1|$ (eq 18 and diagram Figure 4 ($\mathcal{S}_1$)) and the classical signal, $|\tilde{S}^{(c)}|$ (their sum), are displayed from left to right. The signals are computed for a two-level vibronic model system with ground and excited states, each having $N = 11$ vibrational states. Red and dashed blue markers indicate allowed vibrational transitions in the ground and excited manifolds, respectively. The interstate vibronic dephasing rate is $\gamma_{e_{n_e}g_{n'}} = \gamma_{g_n e_{n'}} = 0.01$ eV and intrastate vibrational dephasing rate is $\gamma_{g_n g_{n'}} = \gamma_{e_n e_{n'}} = 0.005$ eV.

$$\mathcal{S}_0(\bar{\omega}_p, \delta\tau_{si}) = -\frac{2\pi C c_{s_2} c_{p_1} c_i \boldsymbol{\epsilon}_s^* \times \boldsymbol{\epsilon}_i^* \cdot \boldsymbol{\epsilon}_p}{3!\hbar^3} \int_{-\infty}^{+\infty} d\omega_s d\omega_p \psi^*(\omega_s, \omega_p - \omega_s)\phi(\omega_p) e^{-i\omega_s\delta\tau_{si} - i\omega_p\delta\tau_p} \int_0^{\infty} d\tau_{12} d\tau_{23} \langle \boldsymbol{V}_L(\tau_{12} + \tau_{23}) \times \boldsymbol{V}_R(\tau_{23}) \cdot \boldsymbol{V}_L^{\dagger}(0) \rangle_s e^{i\omega_s\tau_{12} + i\omega_p\tau_{23}} \tag{15}$$

and

$$\mathcal{S}_1(\bar{\omega}_p, \delta\tau_{si}) = \frac{2\pi C c_{s_2} c_{p_1} c_i \boldsymbol{\epsilon}_s^* \times \boldsymbol{\epsilon}_i^* \cdot \boldsymbol{\epsilon}_p}{3!\hbar^3} \int_{-\infty}^{+\infty} d\omega_s d\omega_p \psi^*(\omega_s, \omega_p - \omega_s)\phi(\omega_p) e^{-i\omega_s\delta\tau_{si} - i\omega_p\delta\tau_p} \int_0^{\infty} d\tau_{12} d\tau_{23} \langle \boldsymbol{V}_L(\tau_{12} + \tau_{23}) \times \boldsymbol{V}_L(\tau_{23}) \cdot \boldsymbol{V}_L^{\dagger}(0) \rangle_s e^{i\omega_s\tau_{12} + i\omega_p\tau_{23}} \tag{16}$$

We note that these rotationally averaged signals do not vanish only if the three polarization vectors $\boldsymbol{\epsilon}_p$, $\boldsymbol{\epsilon}_i^*$, and $\boldsymbol{\epsilon}_s^*$ are not coplanar.

The two quantum signals isolate the two main contributions to the classical signal, as represented by the ladder diagrams in Figures 4 ($\mathcal{S}_0^1$) and 4 ($\mathcal{S}_0^2$). Such selectivity is not possible by classical spectroscopy. In the ladder diagrams of Figures 4 ($\mathcal{S}_0^1$) and 4 ($\mathcal{S}_0^2$), it is assumed that the central frequencies of the pulses $\mathbf{P}_1$ ($\bar{\omega}_p$) and $\mathbf{I}$ ($\bar{\omega}_i = \bar{\omega}_p - \bar{\omega}_s$) are in the UV regime, resonant with intermanifold vibronic transitions and that of $\mathbf{S}_2$ ($\bar{\omega}_s$) in the IR regime, resonant with intramanifold vibrational transitions. The time interval τ_{12} in $\mathcal{S}_0$ and $\mathcal{S}_1$ (eqs 15 and 16, respectively), which gives information on excited and ground state vibrational coherence, can be measured with the temporal resolution limited only by the entanglement time (T_e) by scanning $\delta\tau_{si}$. The time interval τ_{23} gives information about the intermanifold vibronic coherence. Close to the CW limit, $\sigma_p \gg 1$, one can select a specific vibronic state, $|e_n\rangle$, by tuning central frequency of the pumps ($\bar{\omega}_p$).

Below the quantum signals, S_0 and S_1 are displayed by a half Fourier transform with respect to $\delta\tau_{si}$,

$$\tilde{S}_{0/1}(\bar{\omega}_p, \Omega_{si}) = \int_0^{\infty} d\delta\tau_{si} e^{i(\Omega_{si} + \bar{\omega}_s)\delta\tau_{si}} \mathcal{S}_{0/1}(\bar{\omega}_p, \delta\tau_{si})$$

The sum over states expressions for the quantum signals are given by

$$\tilde{S}_0(\bar{\omega}_p, \Omega_{si}) = \tilde{C} I_p \sum_{n_e, n_e'} \frac{1}{\bar{\omega}_p - (\omega_{e_{n_e}} - \omega_{g_1}) + i\gamma_{e_{n_e}g_1}} \times \frac{\boldsymbol{\mu}_{e_{n_e'}e_{n_e}} \cdot \boldsymbol{\mu}_{g_1 e_{n_e'}} \times \boldsymbol{\mu}_{e_{n_e}g_1}}{\Omega_{si} - (\omega_{e_{n_e}} - \omega_{e_{n_e'}}) + i\gamma_{e_{n_e}e_{n_e'}}} \tag{17}$$

and

$$\tilde{S}_1(\bar{\omega}_p, \Omega_{si}) = -\tilde{C} I_p \sum_{n_e, n_g} \frac{1}{\bar{\omega}_p - (\omega_{e_{n_e}} - \omega_{g_1}) + i\gamma_{e_{n_e}g_1}} \times \frac{\boldsymbol{\mu}_{g_1 g_{n_g}} \cdot \boldsymbol{\mu}_{g_{n_g} e_{n_e}} \times \boldsymbol{\mu}_{e_{n_e}g_1}}{\Omega_{si} - (\omega_{g_{n_g}} - \omega_{g_1}) + i\gamma_{g_{n_g}g_1}} \tag{18}$$

where we have grouped all the inessential factors from eqs 15 and 16 into $\tilde{C}$. Moreover, we have introduced phenomenological dephasing rates $\gamma_{\sigma_n\sigma_{n'}}$. We also assumed $\gamma_{\sigma_n\sigma_{n'}} T_e \ll 1$ and $\sigma_p^{-1} \approx 0$.

The sum over states expression for the classical signal derived in Supporting Information is

$$\tilde{S}^{(c)}(\bar{\omega}_p, \Omega_{si}) = \bar{C} I_p^{3/2} \sum_{n_e} \frac{1}{\bar{\omega}_p - (\omega_{e_{n_e}} - \omega_{g_1}) + i\gamma_{e_{n_e}g_1}} \times \left(\sum_{n_e'} \frac{\boldsymbol{\mu}_{e_{n_e'}e_{n_e}} \cdot \boldsymbol{\mu}_{g_1 e_{n_e'}} \times \boldsymbol{\mu}_{e_{n_e}g_1}}{\Omega_{si} - (\omega_{e_{n_e}} - \omega_{e_{n_e'}}) + i\gamma_{e_{n_e}e_{n_e'}}} - \sum_{n_g} \frac{\boldsymbol{\mu}_{g_1 g_{n_g}} \cdot \boldsymbol{\mu}_{g_{n_g} e_{n_e}} \times \boldsymbol{\mu}_{e_{n_e}g_1}}{\Omega_{si} - (\omega_{g_{n_g}} - \omega_{g_1}) + i\gamma_{g_{n_g}g_1}} \right) \tag{19}$$

Note that the classical signal (eq 19) scales with the input intensity as $I_p^{3/2}$, whereas the quantum signals (eqs 17 and 18) scale as I_p and therefore are enhanced at low intensities.

We now compare the quantum signals and the classical DFG signals for the model system shown in Figure 2. It consists of two energy level manifolds, the ground and excited states, each with $N = 11$ vibrational states. The model system parameters are chosen as follows. The energy gap between the lowest vibrational state in the ground electronic manifold and the lowest vibrational state in the excited electronic manifold is 2 eV. Intramanifold vibrational transitions are in the range 0.14−0.35 eV (see red and blue markers of Figure 5). Components of intermanifold vibronic transition dipole moment vectors are chosen randomly from the normal distribution with zero mean and 1 D standard deviation. Intramanifold transitions between

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vibrational states with energy gaps less than 0.12 eV are neglected, and the remaining transition dipole moment vector components are chosen randomly from the normal distribution with zero mean and 1 D standard deviation.

The quantum signals $\mathcal{S}_0$ and $\mathcal{S}_1$ and the classical signal $\mathcal{S}^{(c)}$ (eqs 17, 18, and 19, respectively) are displayed in Figure 5. In both the classical signal in eq 19 and the quantum signals in eqs 17 and 18, $\bar{\omega}_p$ scans the inter manifold vibronic transitions ($\omega_{e_n} - \omega_{g_1}$). The classical signal in eq 19 shows resonances at $\omega_{e_n} - \omega_{e_{n'}}$ and $\omega_{g_n} - \omega_{g_1}$ when Ω_{si} is scanned, but these resonances are separated in the quantum signals. $\tilde{\mathcal{S}}_0$ isolates the resonances $\omega_{e_n} - \omega_{e_{n'}}$, whereas $\tilde{\mathcal{S}}_1$ isolates the resonances $\omega_{g_n} - \omega_{g_1}$. This is because in the ladder diagrams, Figure 4 ($\mathcal{S}_0^1$), with evolution of excited state vibrational coherences during second time delay, and Figure 4 ($\mathcal{S}_1$), with evolution of ground state vibrational coherences during second time delay, are selected by $\mathcal{S}_0$ and $\mathcal{S}_1$, respectively. But, both these diagrams contribute to the classical signal $\mathcal{S}^{(c)}$. This is clear from Figure 5, where resonances features in $\tilde{\mathcal{S}}^{(c)}$ are separately monitored by $\tilde{\mathcal{S}}_0$ and $\tilde{\mathcal{S}}_1$. From Figure 5, we see that only low-frequency ($\Omega_{si} < 1800$ cm^{-1}) excited state vibrational transitions appear in $\tilde{\mathcal{S}}_0$, whereas $\tilde{\mathcal{S}}_1$ also contains high frequency vibrational transitions. Moreover, various vibronic−vibrational resonances occurring in the region $\bar{\omega}_p \approx$ 2.25−2.4 eV and $\Omega_{si} \approx$ 1000−1800 cm^{-1} in $\tilde{\mathcal{S}}^{(c)}$ are individually selected by $\tilde{\mathcal{S}}_0$ and $\tilde{\mathcal{S}}_1$ and hence can be interpreted as arising from the vibrational transitions in the excited electronic state and the ground electronic state, respectively. Additional 1D plots demonstrating the advantage of the quantum signals are provided in Figure S2 of the Supporting Information.

The interferometric setup proposed here can be used for selectively probing all of the Liouville space pathways that contribute to ultrafast DFG signals. It can selectively probe the pathways involving vibrational coherences in the excited and ground state manifolds. The time-frequency entanglement can target a specific excited vibronic state while time resolving the dynamics of the vibrational coherences. Due to the linear scaling of quantum signals with pump intensity (as opposed to the higher order scaling of the classical signal), the quantum signals are enhanced for low intensities. The Liouville space pathway selectivity offered by this technique is demonstrated for a model system and by comparing the quantum signals to the classical signal. We note that we have assumed a single photon pulse; however, the proposed experiment can be done with a laser pulse prepared in a low intensity coherent state.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.jpclett.3c02341.

Detailed description of the light state preparation, the coincidence measurement and the classical DFG signal, and additional 1D plots of the quantum and classical signals (PDF, ZIP)

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Notes

The authors declare no competing financial interest.

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