Quantum spectroscopy with undetected photons

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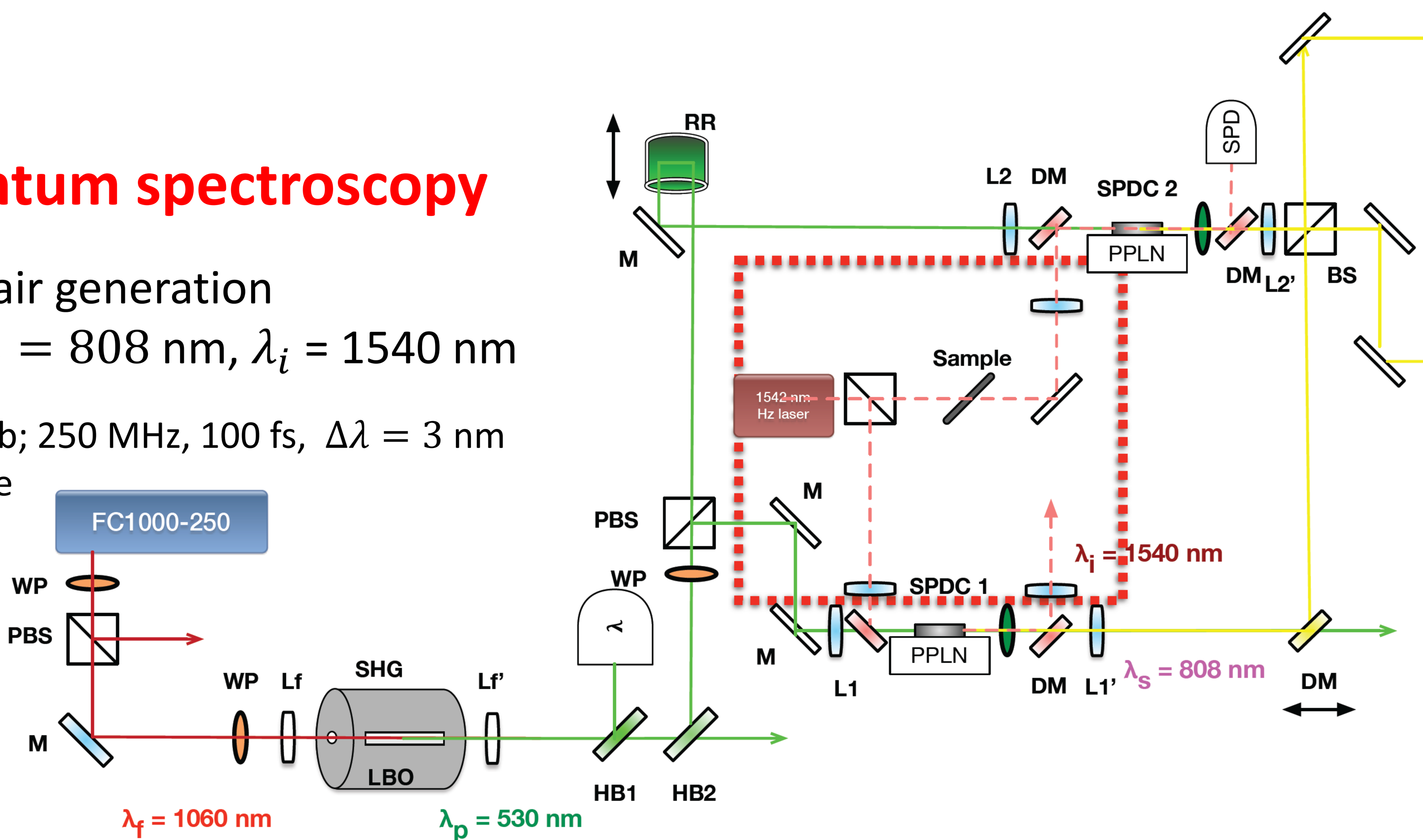
Objectives & Features

- Demonstration of high-resolution quantum spectroscopy with path-entangled non-degenerated down-converted photons.
- We used 530 nm optical frequency comb (and/or cw laser) as a pump sources for type-0 SPDC generation at 808 nm (signal) and 1540 nm (idler) photons.
- **Induced Coherence**: Two idler beam path was aligned in position & time to make idler photons indistinguishable to create an induced coherence of two signal photons.
- **Stimulated Coherence**: A 1-Hz coherent laser at 1540 nm (seed) was injected for both SPDC crystals to stimulate both the idler and signal photons with an increased two-photon pair generation rate proportional to the coherent amplitude $\boldsymbol{\alpha}$ of the seed beam.
- Thus "stimulated coherence quantum spectroscopy" pumped by a frequency comb, demonstrated in this study for the first time, should find wide applications in precision spectroscopy, where non-degenerate light-matter interaction & detection wavelength is essential [5].
- In addition, increased generation of path entangled photon-pair in our stimulated coherence set-up allowed us to measure 1st-order interference fringe by photo detector, also applicable for quantum information processing.
- A Fabry-Pérot cavity is inserted in the midway path of idler photons and detect 1st-order interference spectrum at signal wavelength to measure the frequency resolution of the system (on going experiment).
- Possible extension to multi-dimensional entangled quantum system [6].

Experimental Setup for
Stimulated coherence quantum spectroscopy

Non-degenerate single-photon pair generation
with two type-0 SPDC crystals; λ_s = 808 nm, λ_i = 1540 nm

- Pump; 530 nm optical frequency comb; 250 MHz, 100 fs, $\Delta\lambda$ = 3 nm
- Type-0 SPDC crystal; MgO:PPLN, e-e-e
  L = 15 mm, Λ = 7.5 μm, T = 122 ℃
- Seeding laser; 1 Hz cw laser
  P = 10 mW, injection locked DBR LD
- Detector; EMCCD (w/o EM function), BW = 100 Hz (adjustable ROI)



Entangled photon pair generated by two SPDCs

1. Hamiltonian

$$H = i\hbar g_k V a^\dagger_{s_k} a^\dagger_{i_k} + h.c$$

2. Time dependent state

$$|\psi(t)\rangle = e^{-iHt/\hbar}|0\rangle = \{1 + gtV(a^\dagger_s a^\dagger_i - hc)\}|0\rangle + \cdots$$

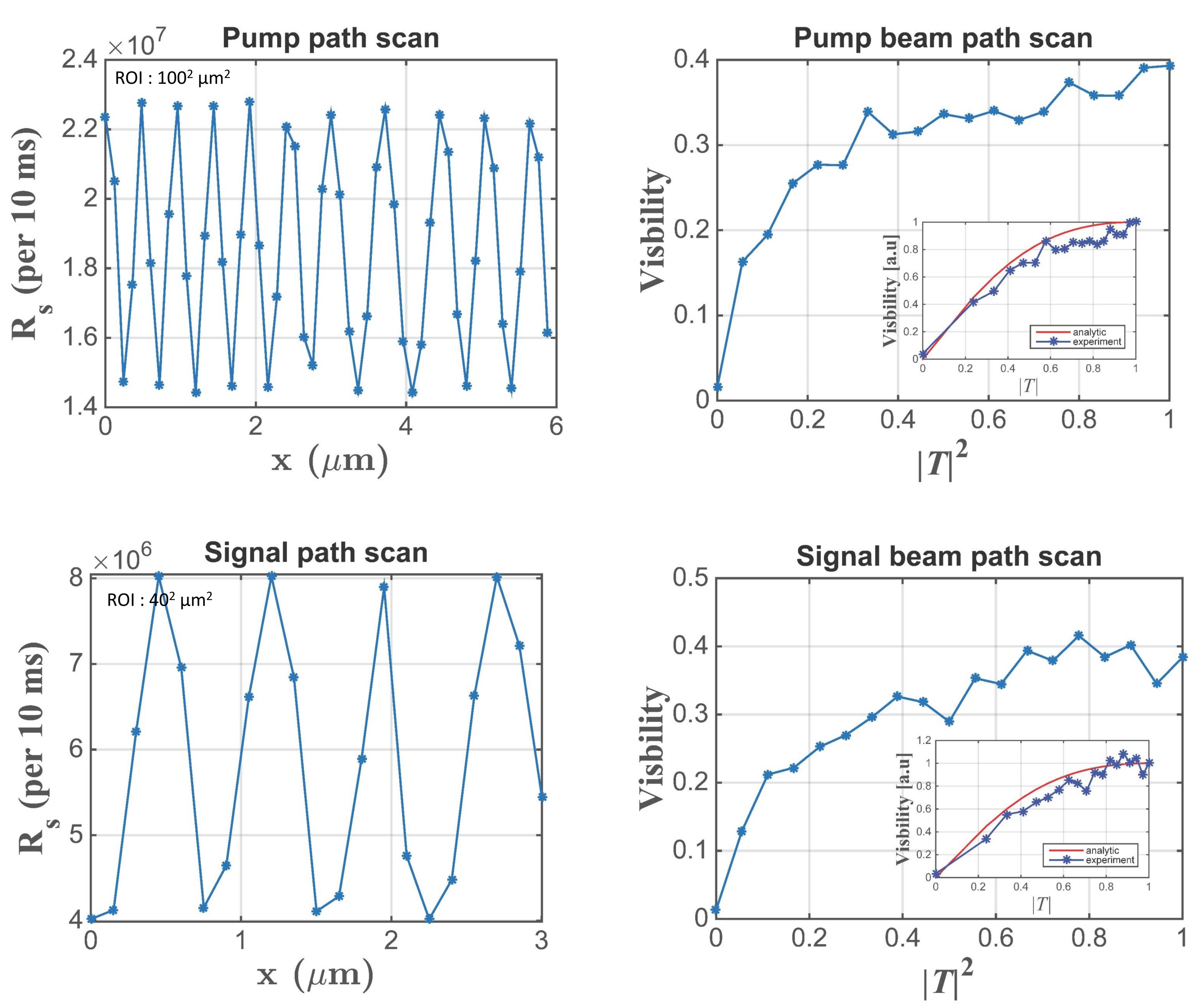
3. Quantum state of photon pair

$$|\psi(t)\rangle_{s,i} \approx |00\rangle + gVt|11\rangle$$

4. Quantum state of photon pairs in two NL crystals

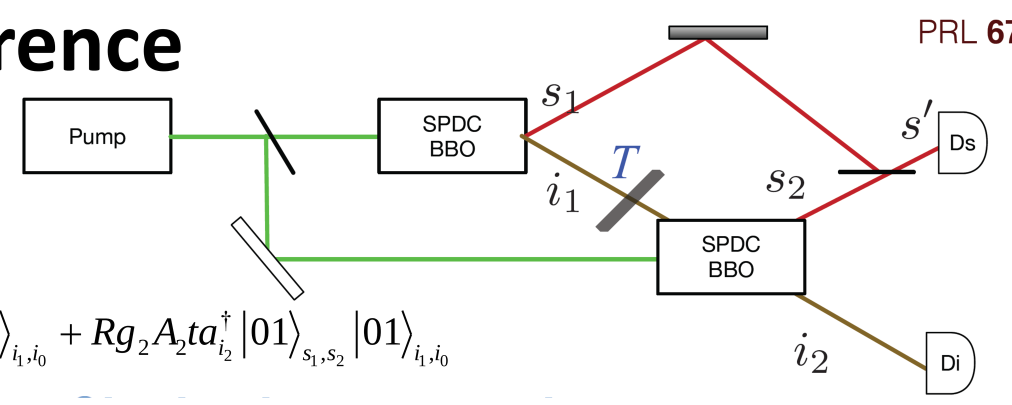
$$|\psi(t)\rangle_{s_1,i_1,s_2,i_2} \approx |0000\rangle + gVt(|1100\rangle + |0011\rangle)$$

Experimental Results



- At high α, contrasts approach C = 50 %, for pump & signal phase changes
- Visibility follow the stimulated coherence model for both phase changes

Induced & stimulated coherence



PRL **67**, 318 (1991)

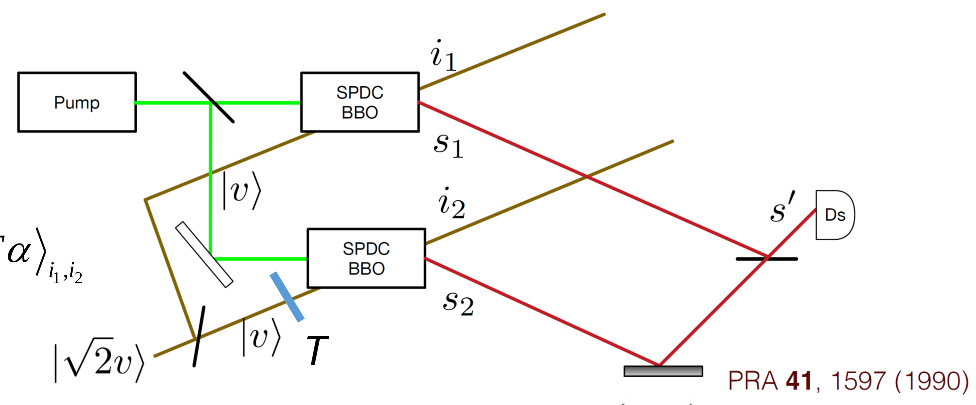
- Induced coherence $(\alpha = 0,\ a_{i_2} = Ta_{i_1} + R^* a_{i_0})$ [1]

(1) Quantum state

$$|\psi\rangle \approx |00\rangle_{s_1,s_2}|00\rangle_{i_1,i_0} + \left(g_1 A_1 t|10\rangle_{s_1,s_2} + T^* g_2 A_2 t a^?_{i_2}|01\rangle_{s_1,s_2}\right)|10\rangle_{i_1,i_0} + Rg_2 A_2 t a^\dagger_{i_2}|01\rangle_{s_1,s_2}|01\rangle_{i_1,i_0}$$

(2) Single photon counting rate & visibility

$$R_s \propto \langle\psi|(a_{s_1} + e^{i\theta}a_{s_2})(a^\dagger_{s_1} + e^{i\theta}a^\dagger_{s_2})|\psi\rangle = 2(1+|T|\cos\theta),\quad V = |T|$$



PRA **41**, 1597 (1990)

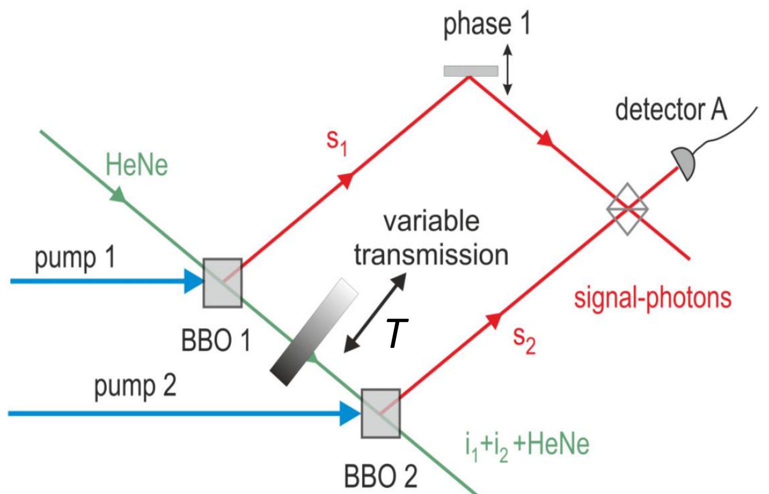
- Stimulated coherence $(\langle n\rangle = |\alpha|^2 >> 1)$ [2]

(1) Quantum state

$$|\psi\rangle \approx |00\rangle_{s_1,s_2}|\alpha,T\alpha\rangle_{i_1,i_2} + g_1 A_1 t a^\dagger_{i_1}|10\rangle_{s_1,s_2}|\alpha,T\alpha\rangle_{i_1,i_2} + g_2 A_2 t a^\dagger_{i_2}|01\rangle_{s_1,s_2}|\alpha,T\alpha\rangle_{i_1,i_2}$$

(2) Single photon counting rate & visibility

$$R_s \propto 2 + |\alpha|^2 + |T\alpha|^2 + 2T|\alpha|^2\cos\theta,\quad V = \frac{2T}{1+|T|^2}$$



- Stimulated & Induced coherence $(a_{i_2} = Ta_{i_1} + R^* a_{i_0},\ |\alpha|^2 >> 1)$ [3]

(1) Quantum state

$$|\psi\rangle \approx |00\rangle_{s_1,s_2}|\alpha,0\rangle_{i_1,i_0} + \left(g_1 A_1 t a^\dagger_{i_1}|10\rangle_{s_1,s_2} + g_2 A_2 t T a^\dagger_{i_1}|01\rangle_{s_1,s_2}\right)|\alpha,0\rangle_{i_1,i_0} + g_2 A_2 t|01\rangle_{s_1,s_2}|$$

(2) Single photon counting rate & visibility

$$R_s \propto (1+|T|^2 + 2T\cos\theta)(|\alpha|^2+1) + |R|^2,\quad V \cong \frac{2T}{1+|T|^2}$$

PRA 92, 033834, (2015)

$$\Rightarrow V \cong \frac{2T}{1+|T|^2},\ I(\emptyset) = I_0\left[1 + V\,\mathrm{Cos}(\emptyset_p + \emptyset_s + \emptyset_i)\right]$$

Discussions & Outlooks

- In our quantum interferometry, signal photon coherence has been created by a cw seed laser and the information of optical sample located in one of the idler path has been measured by the first-order interference of the signal photons with a CCD detector.
- Stimulated coherence quantum interferometer would be applied for quantum imaging [4] and spectroscopy [5] with undetected photons .

References & Acknowledgement

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