Frequency Comb single photon interferometry for optical measurement with undetected photons

Sun Kyung Lee[1], Tai Hyun Yoon[1,2], and Minhaeng Cho[1,3]

[1]*Center for Molecular Spectroscopy and Dynamics, Institute for Basic Science (IBS), Seoul 02841, Republic of Korea.*
[2]*Department of Physics, Korea University, Seoul 02841, Republic of Korea*
[3]*Department of Chemistry, Korea University, Seoul 02841, Republic of Korea*

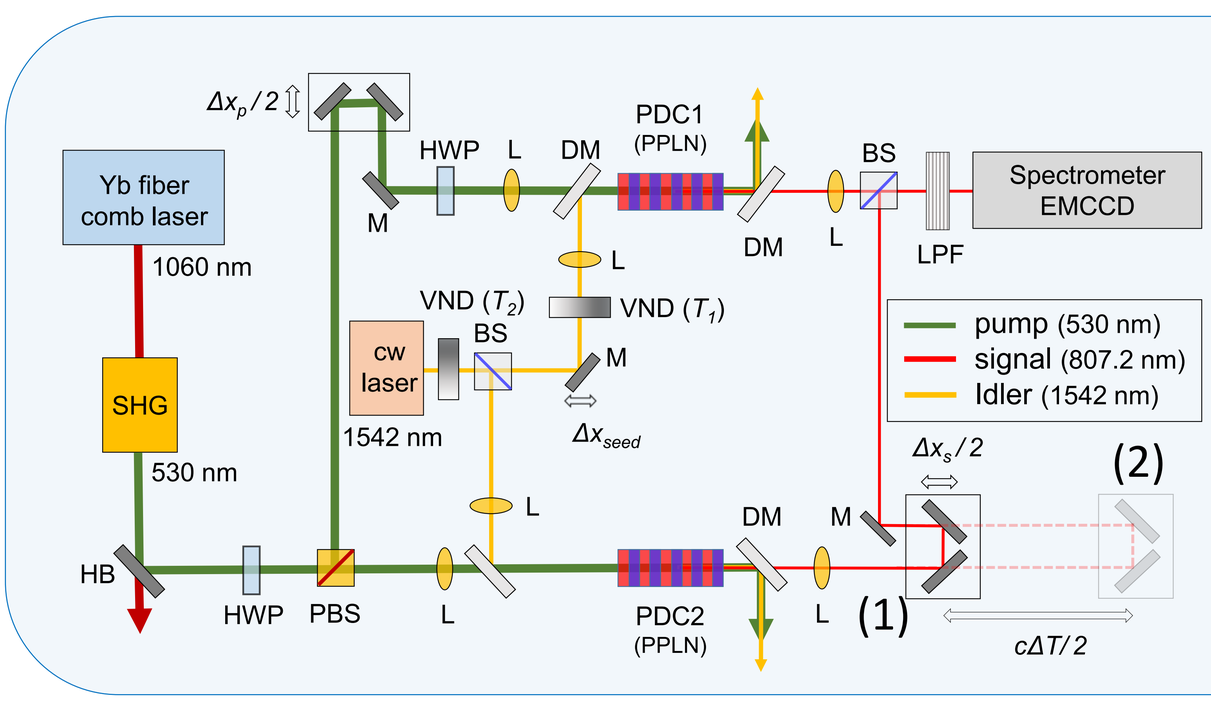
Abstract

Optical frequency comb with the advent of mode-locked femtosecond lasers has revolutionized precision metrology, high-resolution spectroscopy, and ultrafast molecular imaging. Independently, quantum-entangled photons have been widely used in quantum information science & technology and recently enabled scientists to develop quantum spectroscopy and imaging with undetected photons. Here, we apply the two techniques to construct a frequency-comb single-photon interferometry (FC-SPI) with dual parametric down-conversions pumped by highly-stable frequency comb laser and stimulated by ultra-narrow coherent laser. We show that the quantum coherence of single-photons with frequency comb characteristics can be induced by erasing which-path information of a pair of entangled photons. High-visibility quantum interference of either path-entangled or time-bin encoded single-photons with multiple frequency comb components is observed. We anticipate that the FC-SPI greatly impacts on the newly emerging frequency-comb-based quantum information technology and on various quantum optical measurements due to its intrinsic long-term coherence in time domain and scalability in frequency domain.

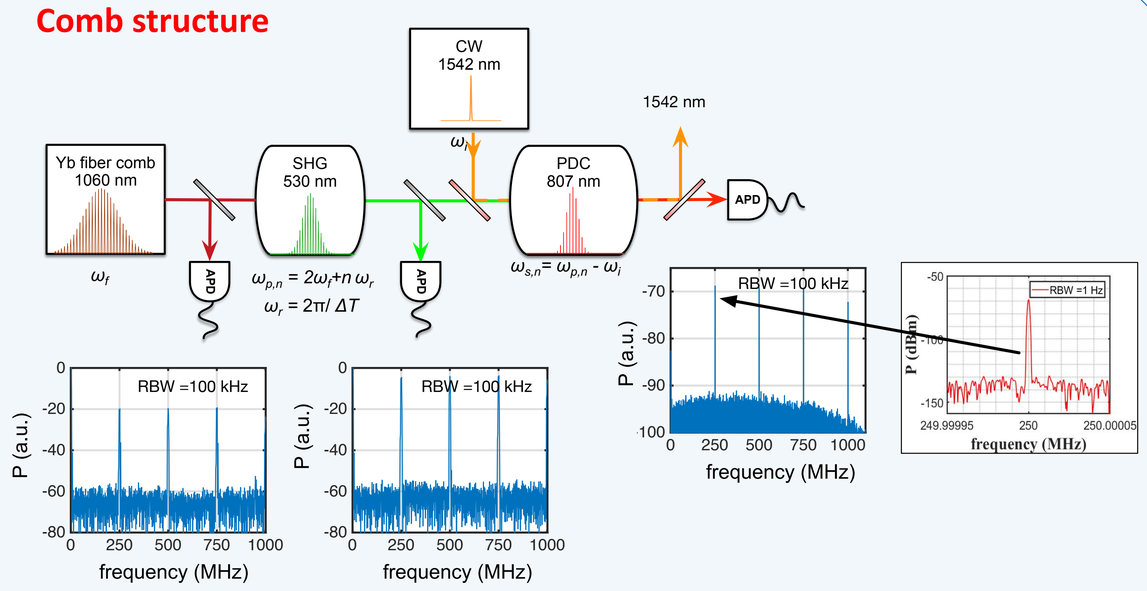
Theoretical description

- **Hamiltonian** $H = \int dV\ g \sum_{k_s} \sum_{k_i} G(\omega_s,\omega_i) e^{-i(k_s+k_i)z}\, \hat{a}_i^\dagger(\omega_i)\hat{a}_s^\dagger(\omega_s) e^{ik_p(\omega_p)z} e^{i(\omega_s+\omega_i)t} E_p(t) + h.c.$
- **Pump (pulse train)** $E_p(t) = \sum_{n=-\infty}^{\infty} A(t-n\Delta T) e^{-i(\omega_p(t-n\Delta T)+n\Delta\phi_{ceo})} = e^{-i\omega_p t}\sum_n A_n e^{-i2\pi n f_r t}$
- **Initial state** $|\psi(0)\rangle\ ;\ |0\rangle_{s_1}|\alpha_1(\omega_i)\rangle_{i_1}|0\rangle_{s_2}|\alpha_2(\omega_i)\rangle_{i_2}$
- **Quantum state**
$$|\psi_2(t)\rangle \approx |0\rangle_{s_1}|\alpha_1(\omega_i)\rangle_{i_1}|0\rangle_{s_2}|\alpha_2(\omega_i)\rangle_{i_2} + \sum_n g_1 t A_{1,n}\, \hat{a}_{i_1}^\dagger(\omega_i)|\omega_{s,n}\rangle_{s_1}|\alpha_1(\omega_i)\rangle_{i_1}|0\rangle_{s_2}|\alpha_2(\omega_i)\rangle_{i_2}|\omega_i,0\rangle_{i_1,i_0}$$
$$+ \sum_n g_2 t A_{2,n}\, \hat{a}_{i_2}^\dagger(\omega_i)|0\rangle_{s_1}|\alpha_1(\omega_i)\rangle_{i_1}|\omega_{s,n}\rangle_{s_2}|\alpha_2(\omega_i)\rangle_{i_2}$$
- **One photon interference**
$$E_s^+ = \sum_n e^{i\varphi_{s_1}}\hat{a}_{s_1}(\omega_{s,n}) + e^{i\varphi_{s2}}\hat{a}_{s_2}(\omega_{s,n})$$
$$\text{and } \alpha_1(\omega_i) = |\alpha(\omega_i)|e^{i\varphi_{i_1}}, \alpha_2(\omega_i) = |T(\omega_i)\alpha(\omega_i)|e^{i\varphi_{i_2}}$$
$$R_s = \sum_n |gtA_n|^2\left(|\alpha(\omega_i)|^2 + |T(\omega_i)\alpha(\omega_i)|^2 + 2 + 2|T(\omega_i)||\alpha(\omega_i)|^2\cos[\Delta\varphi_p + \Delta\varphi_s - \Delta\varphi_{seed}]\right)$$
- **Visibility** $V = \dfrac{2|T(\omega_i)||\alpha(\omega_i)|^2}{|\alpha(\omega_i)|^2 + |T(\omega_i)\alpha(\omega_i)|^2 + 2}$
- **Indistinguishability** $F \equiv \left|{}_{i_1}\langle\alpha_1|\,{}_{i_2}\langle\alpha_2,1|\alpha_1,1\rangle_{i_1}|\alpha_2\rangle_{i_2}\right| = \dfrac{|\alpha_1\alpha_2|}{\sqrt{1+|\alpha_1|^2}\sqrt{1+|\alpha_2|^2}}$

Experimental set-up

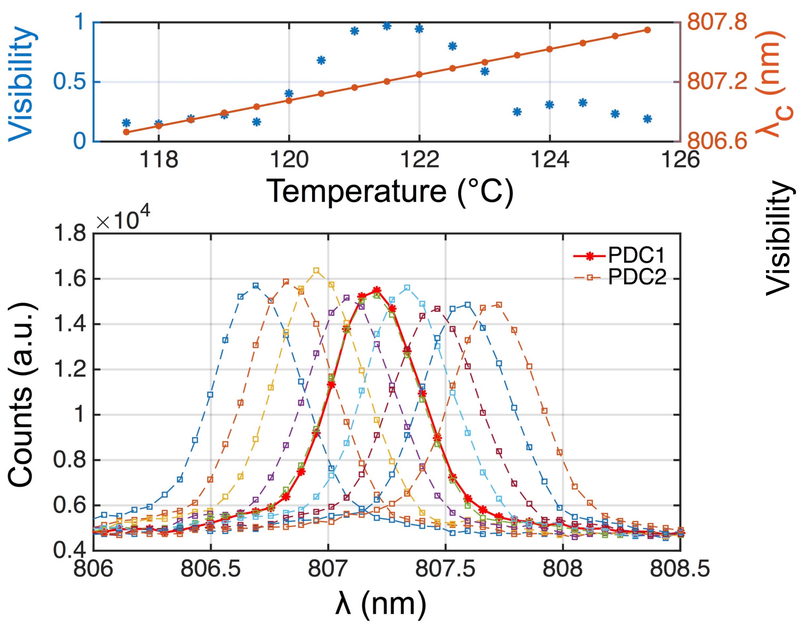


Comb structure

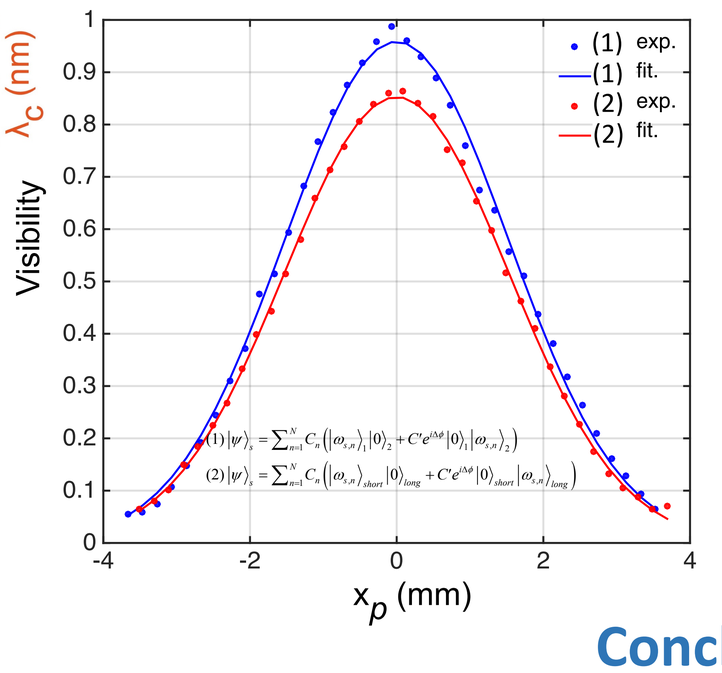


Results

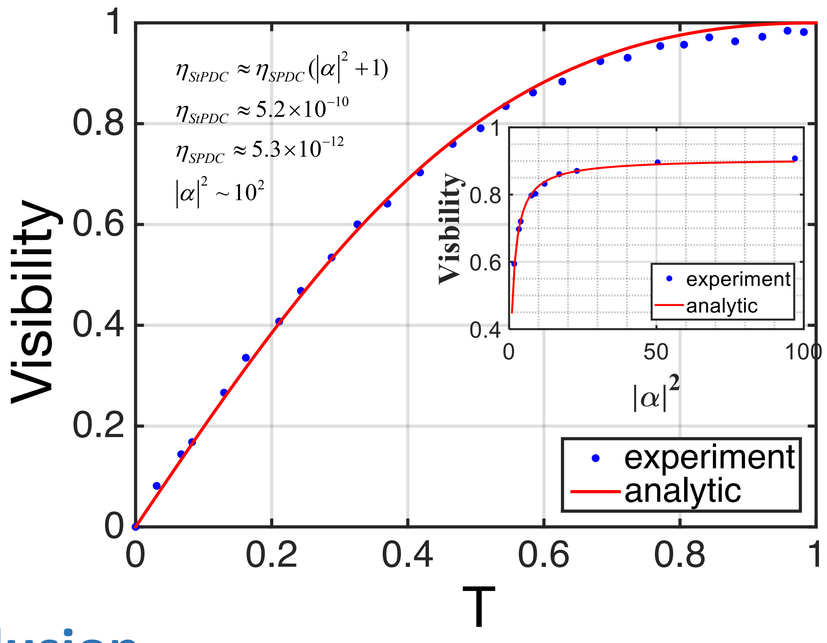
Spectral overlap



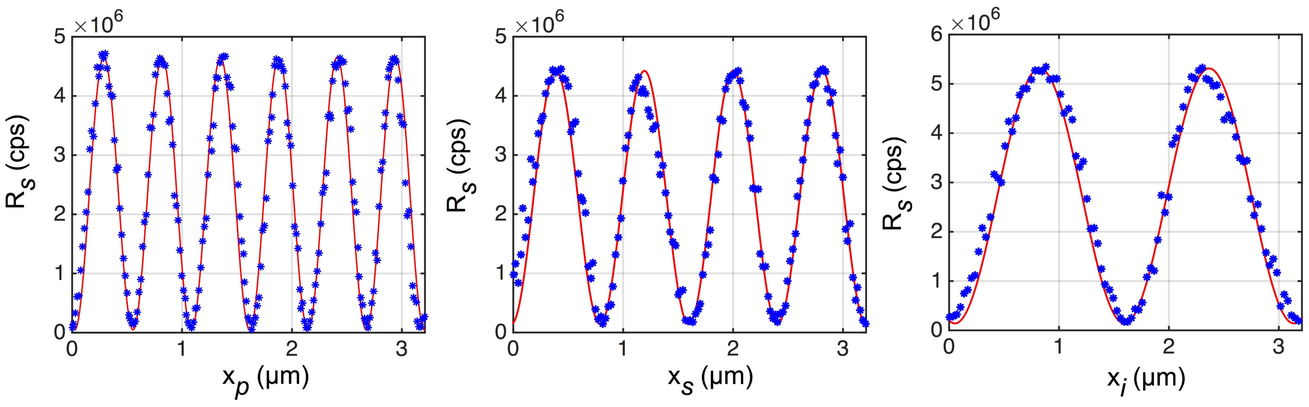
Temporal overlap



Signal photon measurement of idler transmittivity



One photon interference fringe of signal single photons



Conclusion

We note that our frequency-comb single-photon interferometry (FC-SPI) in either spatial or time domain clearly demonstrates that the quantum interference of single-photons with frequency-comb characteristics can be induced by erasing which-path information of a pair of entangled photons in unheralded way. Since the interferometry involves a purely quantum mechanical feature, *i.e.,* single-photons in high-dimensional qudit states and relation between distinguishability and visibility (complementary relation), we anticipate that the FC-SPI greatly impacts on the newly emerging frequency-comb-based quantum information technology and on various quantum spectroscopy and imaging beyond classical limit.