# 진동수 얽힘상태 광자쌍의 간섭

# Two-photon interference experiment with frequency-entangled photon pairs

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Two or more particle entangled states are play an important role opening the new field of quantum optics, for example, two-photon engineering, imaging, cryptography, teleportation, communication, and computing. During the last two decades, there are many experimental efforts to study the fundamental properties of two or more particles in an entangled states. Among them, most of experiments have been carried out in two-photon interference employing correlated pair of photons generated by spontaneous parametric down conversion process. In this work, we present another experimental observations of nonclassical and nonlocal interference effect with frequency-entangled photon pairs. Frequency entangled pairs are prepared in noncollinear type-I parametric down-conversion and two-photon interference are observed by monitoring the coincidence counting with varying the path-length difference or the relative time delay between two photons.

Let's consider two *spatially separated* but *entangled* photon pairs with different frequencies $\omega_1$ and $\omega_2$ emitted from the same source (PDC) as illustrated in Fig. 1. If one photon with frequency $\omega_1(\omega_2)$ is emitted along the signal path, then the conjugate photon with frequency $\omega_2(\omega_1)$ is emitted along the idler path simultaneously. The signal photon with frequency $\omega_1$ and idler photon with $\omega_2$ are reflected by two mirrors $M_1$ and $M_2$ to a common beam splitter (BS), from which they proceed to two detectors $D_1$ (or $D_1'$) and $D_2$ (or $D_2'$). Similarly, the signal with $\omega_2$ and idler with $\omega_1$ are reflected from two mirrors to the BS, from which they proceed to two detectors. In this arrangement, the two photons with different frequencies do not arrive at the BS at the same point, which can be confirmed with double aperture before BS. In our experiment, frequency(or mode) selection is implemented by the use of two interference filters in front of the two detectors. In practice the passband of the two filters is centered on different frequencies $\omega_1$ and $\omega_2$ or on conjugate wavelengths of 630.5 nm and 671 nm and both filters have the bandwidth of 10 nm. Therefore, the two frequency components do not overlap in spectral width, so that each detector responds to different frequency components $\omega_1$ and $\omega_2$ from the down-converter.

In quantum theory, the frequency-entangled two-photon states are represented by the form

$$|\Psi\rangle_{\omega_1,\omega_2}=\frac{1}{\sqrt{2}}(|\omega_1\rangle_s|\omega_2\rangle_i+|\omega_2\rangle_s|\omega_1\rangle_i). \quad (1)$$

The state $|\Psi\rangle$ is in a linear superposition state of photon pairs. Therefore the two photons in

Eq.(1) are either in the state $|\omega_1\rangle_s|\omega_2\rangle_i$ or in the state $|\omega_2\rangle_s|\omega_1\rangle_i$ but they can not be in these two states simultaneously. The total amplitude registered by two detector pairs is the superposition of the amplitudes associated with each of the two pairs of correlated frequencies (see Fig. 1). Therefore, the quantum mechanical probabilities for the joint detection of each detector pairs $(D_1, D_2')$, $(D_1', D_2)$, $(D_1, D_2)$ and $(D_1', D_2')$ are

$$\begin{aligned} P_{D_1,D_2'}(\delta\tau) = P_{D_1',D_2}(\delta\tau) &= \frac{1}{4} - \frac{1}{4}\exp\left(-\frac{\sigma^2\delta\tau^2}{2}\right)\cos(\omega_1-\omega_2)\delta\tau, \\ P_{D_1,D_2}(\delta\tau) = P_{D_1',D_2'}(\delta\tau) &= \frac{1}{4} + \frac{1}{4}\exp\left(-\frac{\sigma^2\delta\tau^2}{2}\right)\cos(\omega_1-\omega_2)\delta\tau, \end{aligned} \tag{2}$$

where $\sigma$ is the average spectral bandwidth of the two interference filters. By monitoring the coincident count rates while varying the relative time delay $\delta\tau$, interference fringes will be exhibited. If there is an additional phase shift $+\pi/2$ between two amplitudes in an arrangement corresponding to Eq. (2), then the joint detection probability of detector pair $D_1, D_2'$ is

$$P_{D_1,D_2'}(\delta\tau) = \frac{1}{4} + \frac{1}{4}\exp\left(-\frac{\sigma^2\delta\tau^2}{2}\right)\sin(\omega_1-\omega_2)\delta\tau. \tag{3}$$

This phenomenon is a consequence of the entanglement of the frequency components of the two photons, and of the superposition of indistinguishable probability amplitudes within the interferometer.

In this experiment we observed the interference effects between frequency-entangled photon pairs generated by the parametric down-conversion, and presented a direct verification of the two joint probabilities depending on the arrangement of the detector pairs and the phase shift between two-photon probability amplitudes. The scheme and the observed interference effect may be used for the entanglement based frequency division multiplexer and the Bell-state measurements based on the frequency post-selection rather than polarization. In conclusion, the results obtained by this experiment may provide more understanding of two-photon entanglement and of the interference effect from superposition of the indistinguishable two probability amplitudes.

This work was supported by Korea Research Foundation Grant (KRF-99-041-D00220).

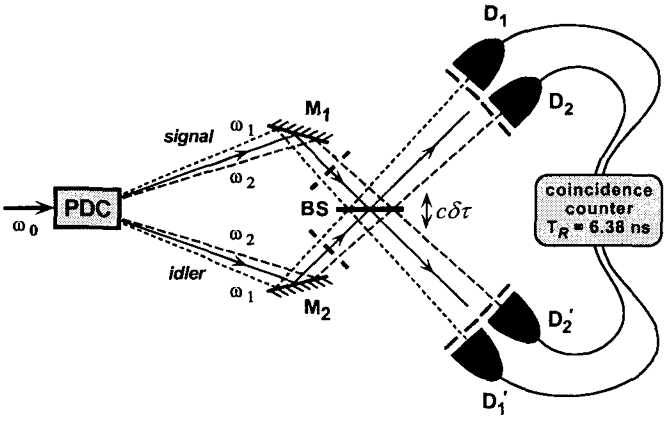

Figure 1. Schematic of the experiment.

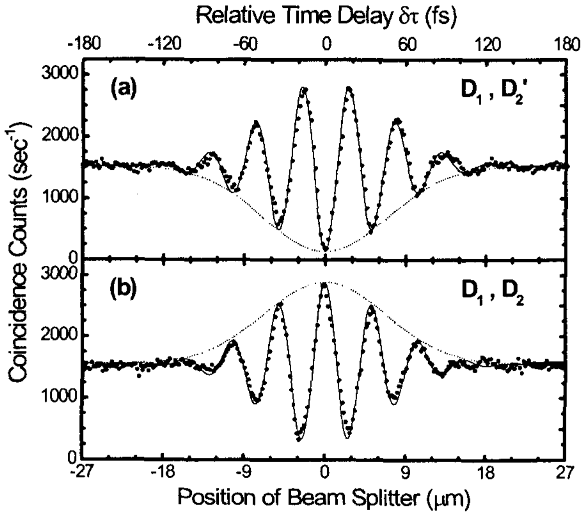

Figure 2. Experimental results.