Manipulating optical qubits in the frequency domain

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During the past years, we have shown that radio-frequency phase modulation of frequency entangled photons leads to a high-dimensional two-photon interference pattern in the frequency domain. By using periodic frequency filters, photons can be grouped into "even" and "odd" frequencies, thereby reducing the high-dimensional photon state to a two-dimensional photon state. We show that a new interference pattern arises when these qubits are made to interfere in the frequency domain, and that this interference pattern exhibits a high visibility and violates the standard two-dimensional Bell inequality, the CHSH inequality. This is realized with components adapted to fiber quantum communication at telecommunication wavelengths.

Introduction

Entangled photon pairs are an essential resource to achieve quantum communication protocols, such as quantum key distribution or quantum teleportation. [1] Photons entangled in energy and time have been extensively studied because they are conveniently produced – possibly at telecommunication wavelengths – by pumping a nonlinear crystal or waveguide. They can also be efficiently manipulated in various ways, for example as *time bins* [2] or as *frequency bins* [3, 4]. Hereafter, we focus on this last method.

As shown in [3, 4], radio-frequency phase modulation of photons belonging to a high-dimensional frequency entangled state leads to a high-dimensional two-photon interference pattern in the frequency domain. While this high dimensionality could be beneficially used, it is sometimes desirable to work with well-known two-dimensional quantum states – qubits – for which most standard quantum information protocols are designed.

Here we first recall the principles behind frequency-bin two-photon experiments, and we show how we can manipulate frequency bins as effective qubits. We then briefly present the experimental setup allowing such a manipulation, and some of our results, including two-dimensional two-photon interference and Bell inequality violation.

Method

An illustrative scheme of frequency-bin two-photon experiments is depicted in figure 1. A continuous laser at frequency ω_P pumping a nonlinear waveguide generates the frequency entangled state

$$|\Psi\rangle = \int d\omega\, f(\omega)\, |\omega_0+\omega\rangle_A\, |\omega_0-\omega\rangle_B\,, \tag{1}$$

with $\omega_0 = \omega_P/2$ for parametric down-conversion in a $\chi^{(2)}$ material, and $\omega_0 = \omega_P$ for four-wave mixing in a $\chi^{(3)}$ material. The function $f(\omega)$ characterizes the source bandwidth.

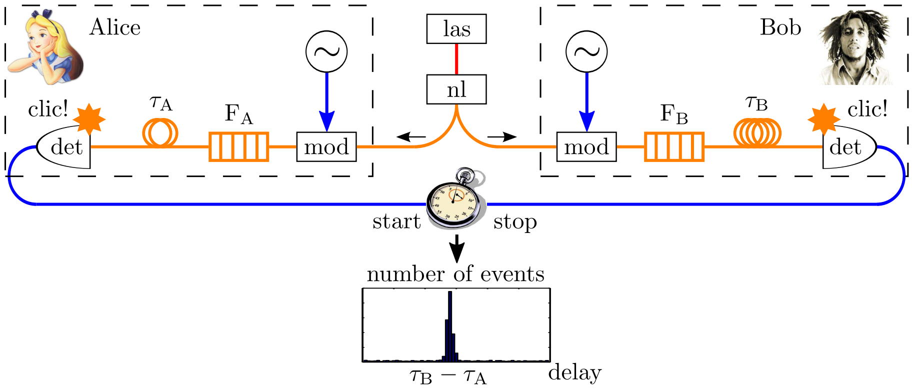

Figure 1: Principle of frequency-bin two-photon experiments. A laser (las) pumps a nonlinear medium (nl), generating frequency entangled photons. Each photon is sent to a different protagonist. It is subject to radio-frequency phase modulation (mod) and passes through a frequency filter ($F_{A,B}$) before detection by a single-photon detector (det). Correlations between detections are analyzed with a histogram of coincident events: when photons are generated simultaneously, a coincidence peak can emerge at a delay $\tau_B - \tau_A$ fixed by the experimenter. When filters are transparent to only a specific frequency $\omega_{A,B}$ and modulation is inactive, a coincidence peak appears only when $\omega_A + \omega_B = 2\,\omega_0$.

The photons are entangled in frequency: the sum of their frequencies is well defined, while their individual frequency is not.
Signal and idler photons are separated, one being sent to Alice (A) and the other to Bob (B). If A and B measure the frequency of their photon, their results are random, the probability of each result being governed by the function $f(\omega)$. On the other hand, the results are perfectly correlated: if A obtains $\omega_0 + \omega$, B obtains $\omega_0 - \omega$ with certainty.
In order to obtain non-trivial correlations, A and B can manipulate their photon before measuring its frequency. This is realized by modulating the phase of each photon with a radio-frequency signal of the form $V(t) = V_{RF}\sin(\Omega_{RF}t - \varphi_{RF})$. Subject to such a signal, a photon state is transformed according to

$$|\omega\rangle \rightarrow \sum_{p\in\mathbb{Z}} U_p\,|\omega + p\,\Omega_{RF}\rangle\ , \quad \text{with}\ \ U_p = J_p\,(\pi V_{RF}\,/\,V_\pi)\ \exp(i\,p\,\varphi_{RF})\,, \tag{2}$$

where J_p is the pth-order Bessel function of the first kind and V_π characterizes the response of the electro-optic phase modulator. The photon therefore ends up in a high-dimensional coherent superposition of different frequencies. Applying transformation (2) to state (1), with $V_A(t) = V_A\sin(\Omega_{RF}t - \varphi_A)$ and $V_B(t) = V_B\sin(\Omega_{RF}t - \varphi_B)$, we obtain

$$|\Psi\rangle \rightarrow \int d\omega' \sum_{\delta\in\mathbb{Z}} |\omega_0 + \omega'\rangle_A\,|\omega_0 - \omega' + \delta\,\Omega_{RF}\rangle_B\,C_\delta\,(V_A,\varphi_A,V_B,\varphi_B)\ , \tag{3}$$

so that the probability $P(\omega_A + \omega_B = 2\,\omega_0 + \delta\,\Omega_{RF}) = |C_\delta\,(V_A,\varphi_A,V_B,\varphi_B)|^2$ is non-zero for different values of δ: a two-photon interference pattern emerges in the frequency domain, and it can be precisely controlled with the parameters $V_A, \varphi_A, V_B, \varphi_B$. [3, 4]
In practice, in order to detect such an interference pattern, A and B must measure the frequency of their photon with a precision better than Ω_{RF}. This is realized by using

filters transparent to only a frequency range $[\omega_{A,B} - \Omega_F/2, \omega_{A,B} + \Omega_F/2]$, with $\Omega_F < \Omega_{RF}$. Photons selected by a filter of bandwidth Ω_F with center frequency $\omega_0 + n\Omega_{RF}$ are said to belong to the *frequency bin n*.

This way to proceed causes, however, a practical problem: the simultaneous measurement of all possible results n_A and n_B would require a large number of cascaded frequency filters, causing high cost and losses. In [3, 4], only two detectors were used, such that the different results could not be measured simultaneously. This has negative consequences for applications. For example, one has to make additional assumptions to demonstrate experimentally Bell inequality violation. [5]

Here, we introduce another way to measure frequency correlations of frequency-bin entangled photons: by using *frequency interleavers*. These periodic filters give access to two outputs corresponding to orthogonal *sets* of frequencies, which we call *even* (E) and *odd* (O) frequencies. We therefore reduce the high-dimensional frequency entangled state to an effective two-dimensional frequency entangled state, see figure 2.

The advantage of such a procedure is that all measurement results are accessible with only four detectors – two for each protagonist. Manipulating effective qubits, we can apply standard procedures for two-dimensional states. For example, simultaneous measurement of all results allows violation – with no further assumption – of the standard two-dimensional Bell inequality, the CHSH inequality. [6]

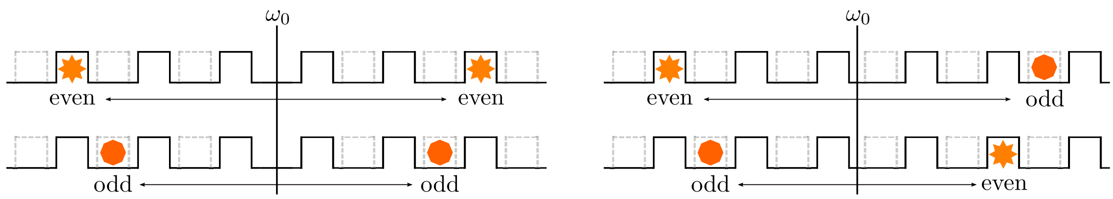

Figure 2: Frequency correlations between signal and idler photons when modulation is inactive. Depicted are the idealized orthogonal outputs of a frequency interleaver: photons with even (continuous dark line) and odd (dotted grey line) frequencies end up in different outputs of the filter. Depending on the position of the degeneracy frequency ω_0, one will observe only EE and OO (left) or EO and OE (right) coincidences.

Experiment

Our experimental setup follows the scheme of figure 1. A continuous laser with power $P \approx 0.7\,\text{mW}$ and stabilized wavelength $\lambda_P = 776.1617\,\text{nm}$ pumps a periodically poled lithium niobate waveguide, generating entangled photons with $\omega_0/2\pi = 193.125\,\text{THz}$ located on the International Telecommunication Union DWDM grid in the C-band.

The photons then pass through a 12.5–25 GHz frequency interleaver from which only one output is collected; this ensures a good orthogonality between E and O subspaces. The photons are separated with a programmable filter which also limits the bandwidth to only a few frequency bins; this guarantees that dispersion is negligible.

The polarization of each photon is controlled with a fiber polarization controller followed by a polarizer, before modulation by a 25-GHz radio-frequency sinusoidal signal with adjustable amplitude and phase. Finally, on each side, a 25–50 GHz interleaver allows collection of E and O results by two avalanche photodiodes. A data acquisition system acquires simultaneously all possible results, i.e. EE, EO, OE and OO coincidences.

Results

Some of our results are presented in figure 3. When modulation is inactive, we obtain, as expected, only EE and OO (for the case shown) coincidences, at a rate $\approx 1.5\,\text{Hz}$ and with a coincidence-to-accidental ratio ≈ 2. These low values are due to high losses and to detector inefficiency. When modulation is active, we observe two-photon interference. The experimental measurements, plotted with statistical error bars and noise subtracted, are in good agreement with the theoretical predictions, which we do not demonstrate here. The interference visibility is about 90%. Colllecting coincidences for some specific settings, we have demonstrated the violation of CHSH inequality by more than 40 standard deviations, therefore demonstrating the presence of frequency entanglement.

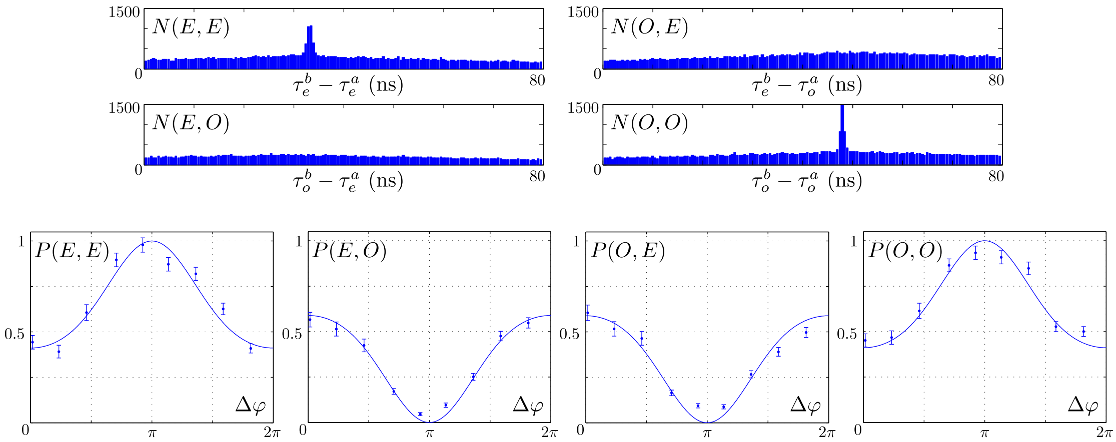

Figure 3: Experimental results. Top: coincidences when modulation is inactive. Bottom: probability of coincidence versus radio-frequency phase shift $\varphi_A - \varphi_B$.

Conclusion

In summary, we have demonstrated the manipulation of effective optical qubits in the frequency domain by using frequency interleavers.

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