Two-photon interference using frequency-bin entanglement

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We present an original method for manipulating frequency entangled photons in standard telecommunication fibers: by using electro-optic phase modulation and narrow spectral filtering a two-photon interference pattern arises directly in the frequency domain. High-visibility measurements show that the radio-frequency parameters controlling the shape of the interference pattern can be very accurately controlled. A theoretical development allows us to calculate radio-frequency parameters leading to the optimal violation of a Bell inequality, which has been experimentally demonstrated. Thanks to these developments we hope to demonstrate in future work the realization of various quantum communication tasks where information is coded with this method.

Introduction

In order to achieve quantum communication in standard optical fibers, entangled photons have to be produced, manipulated, and detected in an efficient way at telecommunication wavelengths. We show that, combined with conventional methods of production (parametric down conversion) and detection (avalanche photodiodes), the method we developed for manipulating frequency entangled photons is a legitimate candidate for the realization of quantum communication protocols at telecommunication wavelengths.

We first theoretically recall our method, which was introduced in [1], and which is based on the notion of *frequency-bin entanglement*. All photons whose frequency belongs to an interval $\left]\omega_F - \frac{\Omega_F}{2}, \omega_F + \frac{\Omega_F}{2}\right]$ are said to be in the same *frequency bin*: their frequency is close enough to the center frequency ω_F of a frequency filter of width Ω_F so that they cannot be distinguished. When frequency-bin entangled photon pairs are sent through electro-optic phase modulators driven by a radio-frequency signal with adjustable parameters, it gives rise in the frequency domain to a two-photon quantum interference pattern. This can be simulated by classical measures, allowing an accurate calibration of the performances of the system. We then calculate what is the optimal violation of a Bell inequality expected with our setup, and present the experimental results linked to this development. We conclude on the use of frequency-bin entanglement in the context of quantum communication at telecommunication wavelengths.

Method

In the experiment of figure 1, a continuous narrow-band laser at frequency $2\omega_0$ pumping a parametric down converter generates the frequency entangled state

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

where $f(\omega)$ is a complex number characteristic of the bandwidth of the signal and idler photons: the sum of their frequencies is determined but individual frequencies are unknown. Each photon is sent through a phase modulator, driven at the radio-frequency Ω_{RF} and with adjustable amplitude a or b and phase α or β, so that

$$|\omega_0+\omega\rangle_A \;\rightarrow\; \sum_{p\in\mathbb{Z}} |\omega_0+\omega+p\Omega_{RF}\rangle_A J_p(a)\, e^{ip(\alpha-\pi/2)}, \tag{2}$$

$$|\omega_0-\omega\rangle_B \;\rightarrow\; \sum_{q\in\mathbb{Z}} |\omega_0-\omega+q\Omega_{RF}\rangle_B J_q(b)\, e^{iq(\beta-\pi/2)}, \tag{3}$$

$J_{p,q}$ being the p,qth-order Bessel function of the first kind. In order to detect interference between frequencies separated by an integer multiple of Ω_{RF}, a coincidence count is realized between photons exiting frequency filters of width $\Omega_F < \Omega_{RF}$ centered on frequencies $\omega_{F_A} = \omega_0 + n\Omega_{RF}$ and $\omega_{F_B} = \omega_0 + (n+d)\Omega_{RF}$. It is indeed shown in [1] that if photon A belongs to a given frequency bin $n \equiv \int_{-\Omega_F/2}^{+\Omega_F/2} d\omega |\omega_0+\omega+n\Omega_{RF}\rangle$, then the probability that photon B belongs to the frequency bin $n+d$ is given, using equations (1,2,3) and some reasonable assumptions, by

$$P_d(a,\alpha;b,\beta) = \left| \sum_{p\in\mathbb{Z}} J_p(a)\, e^{ip(\alpha-\pi/2)} J_{d-p}(b)\, e^{i(d-p)(\beta-\pi/2)} \right|^2. \tag{4}$$

This expression can be simplified to

$$P_d(a,\alpha;b,\beta) = J_d\left\{ \left[a^2+b^2+2ab\cos(\alpha-\beta)\right]^{1/2} \right\}^2 \equiv J_d(C)^2, \tag{5}$$

so that the coincidence rate depends on a single tunable parameter C. It should be noted that when modulation is off ($a=b=0$), $P_{d=0}=1$ and $P_{d\neq0}=0$.

There is an interesting parallel between the experiment of figure 1 and that of figure 2. In the latter, filter F_A selects from a classical broadband source a given frequency bin n, which is consecutively modulated with parameters (a,α) and (b,β). Neglecting variation of the source power with frequency, the optical power detected in frequency bin $n+d$, on which is aligned filter F_B, is expected to be $J_d(C)^2$ times the optical power in frequency bin n when modulation is off. The experiment of figure 2 thus provides a simpler experimental test of the correlations (5) expected in the experiment of figure 1, and allows an easy calibration of the performances of the radio-frequency system used in both experiments. Please note that the setup of figure 2 itself could be used with single photons in order to achieve quantum communication tasks such as quantum key distribution (see [2]).

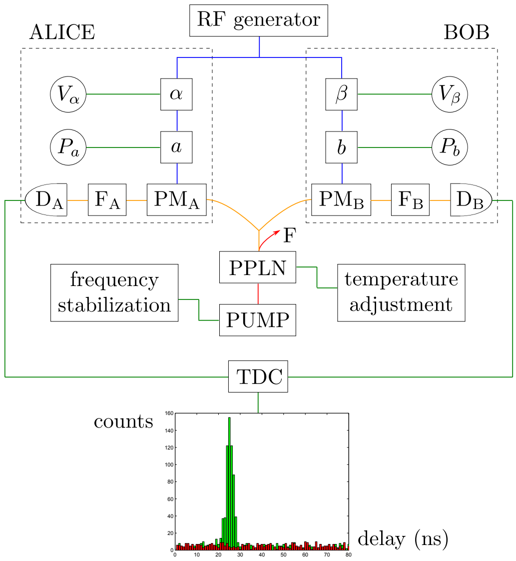

Figure 1: First experimental setup. The frequency of a continuous laser is actively stabilized at the value $2\omega_0 = 387.396$ THz thanks to a PID loop feeded by the signal of a wavelength meter with an absolute accuracy of ± 0.2 ppm and acting on the piezoelectric transducer of the external cavity of the laser. This laser pumps a periodically poled lithium niobate waveguide, phase matching condition being achieved by temperature tuning, so that frequency entangled photon pairs are efficiently generated around $2\pi c/\omega_0 = 1547.73$ nm in a polarization-maintaining telecommunication fiber. A wavelength division multiplexer removes (with 125-dB isolation) the residual energy of the pump laser and a 3-dB coupler separates (with 50% probability) photons A and B, which are sent through an electro-optic phase modulator driven by a radio-frequency signal at $\Omega_{RF} = 25$GHz. Filters F_A and F_B consist of a fiber Bragg grating used in reflection together with a circulator, so that bins $\left]\omega_{F_{A,B}} - \frac{\Omega_F}{2}, \omega_{F_{A,B}} + \frac{\Omega_F}{2}\right]$ restricted to a 3-dB width $\Omega_F \approx 3$GHz are selected. They are detected by avalanche photodiodes D_A and D_B on which a time-to-digital converter performs a coincidence count. The signal-to-noise ratio of the coincidence peak is expected to be a function of the adjustable radio-frequency parameters (i.e. amplitudes a and b and phases α and β of photons A and B, respectively), as predicted by equation (5). The 2.5 GHz signal of a RF generator is split and converted into a 12.5 GHz signal thanks to frequency multiplication and addition. I-Q modulators, whose driving voltage signals V_α and V_β are remotely controlled with a computer, independently adjust Alice's and Bob's phases. The RF signal is amplified and converted to a 25 GHz signal by frequency doublers. Finally, mechanically variable attenuators allow independent adjustment of the RF power P_a and P_b sent to Alice's and Bob's phase modulators, respectively – measures of the power values are realized at the output of 90/10 couplers placed just before the modulators. Independence of Alice's and Bob's parameters is guaranteed by isolators.

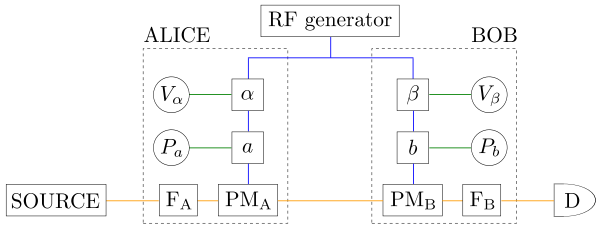

Figure 2: Second experimental setup. The optical part of the experiment consists of a classical broadband source sent through frequency filter F_A, a polarization controller (not shown), a modulator with parameters (a, α), a modulator with parameters (b, β), and filter F_B. A photodetector D measures the optical power.

Results

Experimentally, we focus on the interference described by equation (5) when $d = 0$. In this case, $P_{\max} = 1$ for $a = b$ and $\alpha - \beta = \pi$ and $P_{\min} = 0$ is achievable at sufficiently high powers ($a = b \gtrsim 1.2$). We evaluate $V_{\text{raw}} = \frac{P_{\max}-P_{\min}}{P_{\max}+P_{\min}}$ and $V_{\text{net}} = \frac{(P_{\max}-P_{\text{noise}})-(P_{\min}-P_{\text{noise}})}{(P_{\max}-P_{\text{noise}})+(P_{\min}-P_{\text{noise}})}$. In the case of figure 2, P is the optical power (normalized by the optical power when modulation is off). We obtained values as high as $V_{\text{raw}} \approx 99\%$ and $V_{\text{net}} \approx 100\%$: the fact that we reached the dynamic range of the detector is indication that the RF system allows fine adjustments and that frequency bins are well isolated from each others. In the case of figure 1, P is the signal-to-noise ratio (normalized by the off-value). Because of noisy avalanche photodiodes, we obtained a lower value $V_{\text{raw}} \approx 88\%$, but V_{net} is again near 1.

The correlations (5) allow the violation of a Clauser-Horne type Bell inequality [3, 1], i.e. violation of $P_0(a_0, \alpha_0; b_0, \beta_0) + P_0(a_0, \alpha_0; b_1, \beta_1) + P_0(a_1, \alpha_1; b_0, \beta_0) - P_0(a_1, \alpha_1; b_1, \beta_1) \leq 2$. An optimized value $S = 2.389$ is theoretically obtained for the parameters $(a_0, \alpha_0) = (0.275, \theta) = (b_0, \beta_0), (a_1, \alpha_1) = (0.825, \theta + \pi) = (b_1, \beta_1)$. In this case, $P_0(a_0, \alpha_0; b_0, \beta_0) = 0.857 = P_0(a_0, \alpha_0; b_1, \beta_1) = P_0(a_1, \alpha_1; b_0, \beta_0) = 0.857$ and $P_0(a_1, \alpha_1; b_1, \beta_1) = 0.182$. Both the tests realized with experiment 2, and the actual experiment 1, lead to a value very close to the theoretical one, $S \approx 2.4$.

Conclusion

We have shown that the system we developed allows a reliable manipulation of frequency entangled photons, thanks to its excellent optical and radio-frequency stability, in a potentially fully automated way. We are confident to extend in near future our results to long distance quantum communication in various configurations. We acknowledge support from the Belgian Science Policy under project IAP P6/10, from the French Agence Nationale de la Recherche under project HQNET 032-05, from the Conseil Régional de Franche-Comté, and from PICS-3742 of the French Centre National de la Recherche Scientifique. Thank you to François Leo for having helped us to stabilize our pump laser.

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