Cross-phase modulation of a probe stored in a waveguide for non-destructive detection of photonic qubits

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Non-destructive detection of photonic qubits is an enabling technology for many quantum information processing and quantum communication-related tasks. For example, in quantum repeaters that utilize sources of photon pairs based on spontaneous parametric down-conversion, multi-photon emissions lead to an increased error rate over the case where deterministic photon-pair sources are employed. Non-destructive measurements can be used to identify the events where more than a single pair is produced from the down-conversion source, decreasing the error-rate [1].

For practical applications, it is desirable to implement non-destructive measurement in a way that allows some form of multiplexing as well as easy integration with other components such as solid-state quantum memories. Here we propose an approach to non-destructive photonic qubit detection that promises to have all these mentioned practical features. Mediated by an impurity-doped crystal, a signal photon in an arbitrary time-bin qubit state modulates the phase of an intense probe pulse that is stored during the interaction. We also present a proof-of-principle experiment with macroscopic signal pulses that demonstrates the expected cross-phase modulation as well as the ability to preserve the coherence between temporal modes [2].

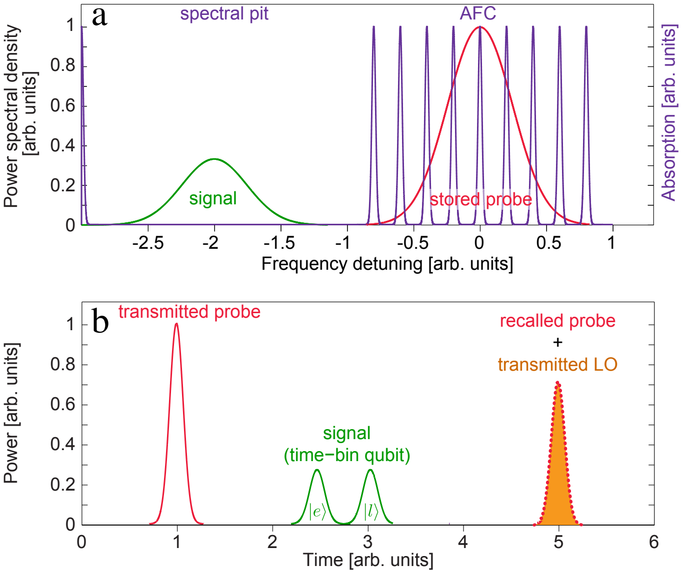

FIG. 1. **Non-destructive detection of photonic time- bin qubits**. A macroscopic probe pulse is stored in an atomic frequency comb (AFC) memory. The signal a photonic time-bin qubit propagates through a detuned transparency window and frequency shifts the atoms constituting the AFC due to the AC Stark effect. This results in a phase shift of the re-emitted probe. **a**, Spectral representation. **b**, Temporal representation. $|e\rangle$ and $|l\rangle$ denote early and late qubit modes, respectively.

The basic principle, illustrated in Fig. (1), is based on cross-phase modulation between a weak signal and a strong probe pulse mediated by a rare-earth ion doped crystal - a technology platform whose suitability for quantum photonics has already been demonstrated. The probe is stored in an impurity-doped crystal using the atomic frequency comb (AFC) quantum memory protocol, and the phase shift is due to the AC Stark shift of the relevant atomic transition caused by the signal. For large detuning between signal and probe, it is given by

$$\phi = N_s \frac{1}{4\pi} \frac{\lambda^2}{n^2 A} \frac{\gamma}{\Delta}, \tag{1}$$

where N_s is the number of photons in the signal, λ the vacuum wavelength of the atomic transition, n the refractive index of the crystal, A the interaction cross section, γ the spontaneous decay rate from the excited state, and $\Delta/(2\pi)$ the detuning.

We emphasize that the phase shift does not depend on the exact timing of the signal, as long as it propagates through the medium while the probe is being stored. In particular, this allows one to detect the presence of a photon without affecting its qubit state, provided that the qubit is encoded in temporal modes a very convenient and widely-used choice in quantum communication.

Our experimental setup consists of a Tm:LiNbO$_3$ waveguide, which we spectrally tailor by optical pumping into a series of peaks (the AFC) surrounded by transparent pits. We then generate a probe pulse that is stored in the AFC followed by a signal pulse whose temporal structure, intensity and detuning w.r.t. the AFC we can vary, depending on the desired measurement. The phase change imprinted on the recalled probe due to interaction with the signal is measured by interfering it with a local oscillator.

First, we verify the probe-phase-shift given in Eq.(1) by varying the intensity and detuning of the signal. Next, we demonstrate that the probe phase shift does not depend on how the signal energy is distributed between two temporal modes, and that the signal is not affected by the measurement. Towards this end, we select two temporal bins denoted by early and late that are separated by 18.3 ns. We then generate a signal pulse with a detuning of +100 MHz and a fixed total energy, which is either in the early or the late mode, or in an equal superposition with either 0 or π phase-difference (+ and - superpositions, respectively). The resulting probe phase shifts, averaged for each pulse sequence over 1000 repetitions, are plotted in Fig. (2), which also includes the phase shift measured without a signal pulse. We find that, within experimental uncertainty, the phase shifts are the same irrespective of the signal state, and they clearly differ from the phase shift measured without any signal. Furthermore, to verify that our measurement preserves the signal state, we assess erroneous detections of signals prepared in various states without and with the measurement. As shown in the inset of Fig. (2), we find close to no change due to the cross-phase interaction, which is consistent with the fact that our scheme can measure the presence of a time-bin qubit without revealing, nor modifying, its state.

We believe that further improvements of our proof-of-principle demostration, such as a reduction of the interaction cross section, e.g. using a small-diameter ridge waveguide, and a higher ratio between the radiative lifetime γ and the detuning Δ, will soon allow "single shot" non-destructive measurement of photons.

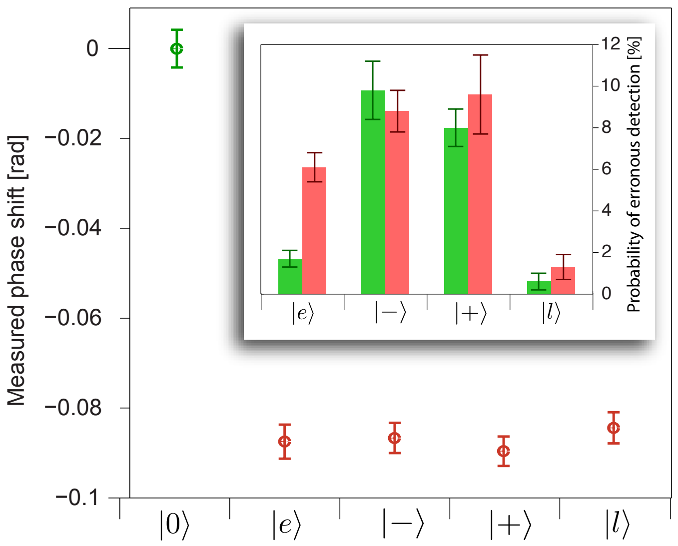

FIG. 2. State preservation for signals in different temporal modes. Probe phase shifts due to $6.9{\times}10^7$, or no, signal photons, distributed between early and late temporal modes. The labels on the x-axis refer to corresponding time- bin qubit states. Each data point shows the average over 1000 measurements, and uncertainty bars denote the standard de- viation of the average. The inset shows the error rates i.e. the ratio of the energy detected in the wrong output mode to the the total energy detected in both the correct and wrong modes of the different signal states before (green bars) and after (red bars) the measurement.(error bars are calculated from shot-to-shot pulse-heights variations). There is no significant change, except for $|e\rangle$. (Increased errors are likely due to free induction decay due to signal pulse. As the decay happens after absorption, only $|e\rangle$ is affected. Errors for the superposition states are caused by imperfections in the interferometer.)

[1] H. Krovi, S. Guha, Z. Dutton, J. A. Slater, C. Simon, W. Tittel, Applied Physics B, 122:52 (2016)

[2] N. Sinclair, K. Heshami, C. Deshmukh, D. Oblak, C. Simon, W. Tittel., Cross-phase modulation of a probe stored in a waveguide for non-destructive detection of photonic qubits, arXiv:1510.01164 (2015).