Proposal and proof-of-principle demonstration of non-destructive detection of photonic qubits using a Tm:LiNbO$_3$ waveguide

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Non-destructive detection of photonic qubits is an enabling technology for quantum information processing and quantum communication. For practical applications, such as quantum repeaters and networks, it is desirable to implement such detection 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 the mentioned 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. Using a thulium-doped waveguide in LiNbO$_3$, we perform a proof-of-principle experiment with macroscopic signal pulses, demonstrating the expected cross-phase modulation as well as the ability to preserve the coherence between temporal modes. Our findings open the path to a new key component of quantum photonics based on rare-earth-ion-doped crystals.
The possibility to detect the presence of a visible or telecommunication-wavelength photon in a non-destructive and state-preserving manner is highly desirable for photonic quantum information processing and quantum networks as it makes it possible to use precious resources (say entangled photon pairs for quantum teleportation) only when required (for example, if the signal photons whose state is to be teleported are actually there). This is all the more essential in cases where significant signal loss occurs, for example, in quantum repeaters. As such, several approaches to non-destructive photon and, exceptionally, non-destructive qubit detection are currently being pursued. For instance, non-destructive detection of photons and heralded storage of photonic qubits (which, when combined with readout, is equivalent to non-destructive qubit detection) have been achieved using single, laser-trapped atoms in high-finesse cavities. Non-destructive detection of optical photons is also being pursued with atomic ensembles, and large single-photon phase shifts mediated by laser-cooled atomic vapour have recently been reported using both Rydberg blockade and the a.c. Stark shift in a high-finesse cavity. The latter system has furthermore enabled partial non-destructive detection of traveling photons. These investigations are part of the general drive of using atomic ensembles to mediate strong photon–photon interactions for, for example, via strong long-range dipole–dipole interaction between Rydberg atoms or via the a.c. Stark shift. Experimental realizations of photon–photon interaction using Rydberg states and the a.c. Stark shift have furthermore enabled applications such as all-optical switching. Finally, we note that non-destructive detection has been achieved for microwave photons inside cavities using superconducting circuits and Rydberg atoms. Currently, the most advanced experiments targeting the detection of optical photons rely on single atoms or cold atomic gases. However, from the point of view of practical applications, it is of interest to investigate implementations in the solid state as well. Ideally, such approaches should preserve the qubit state encoded into the photon, allow for multiplexing and be compatible with existing solid-state quantum information processing and communication components.

Here, we propose a scheme for non-destructive detection of photonic time-bin qubits that has all of these characteristics. After a short theoretical description of our scheme, we detail a proof-of-principle experiment using intense coherent pulses and an impurity-doped crystal that confirms the predictions of our theory. Finally, we discuss how our proposal can be implemented at the single-photon level.

Results

Proposal for quantum non-destructive measurement. The basic principle of our scheme, 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. For single-photon sensitivity, the phase shift has to be greater than the quantum phase uncertainty of the probe, which is of order $\sqrt{N_p}/N_p$, where $N_p$ is the number of photons in the probe. The probe is stored in an impurity-doped crystal using an approach based on atomic frequency combs, and the phase shift is due to the a.c. Stark shift of the relevant atomic transition caused by the propagating signal. For large detuning between signal and probe, it is given by

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

where $N_s$ is the number of photons in the signal, $\lambda$ is the vacuum wavelength of the atomic transition, $n$ is the refractive index of the crystal, $A$ is the transverse mode area of the interaction, $\gamma$ is the spontaneous decay rate from the excited state, $\Delta(2\pi\nu)$ is the detuning in Hz and $\sigma = n^2 \gamma$ is the resonance absorption cross-section of a radiatively broadened transition. See Supplementary Note 1 and Supplementary Fig. 1 for a detailed derivation.

Proof-of-principle demonstration using strong coherent pulses. Our experimental setup, sketched in Fig. 2a, is composed of a Tm:LiNbO$_3$ waveguide, a source for signal and probe pulses, and analyzers that allow characterizing these pulses after the waveguide-mediated interaction. We use the optical pumping sequence illustrated in Fig. 2b to spectrally tailor the inhomogeneously broadened $^3\text{He} \rightarrow ^3\text{H}_2$ absorption line of Tm into a series of absorption peaks (teeth) spaced by angular frequency $\Delta_\text{osc}$, an atomic frequency comb (AFC), surrounded by transparent pits (see Fig. 2c). The bandwidth of the AFC and each of the pits is about 100 MHz, and the storage time of the probe in the waveguide, given by $t_\text{store} = 2\pi/\Delta_\text{osc}$, is 180 ns.

Following the spectral tailoring, we generate a probe pulse of $\sim$10 ns duration whose spectrum matches the AFC. A part of the pulse is transmitted through the waveguide and a part of it is
We see that the measured data closely follow the theoretical predictions derived from equation 1 using \( \lambda = 795\,\text{nm}, n = 2.3, A = \pi \times (6.25\,\mu\text{m})^2, \gamma = 8.1\,\text{kHz} \). In particular, at \( +100\,\text{MHz} \) detuning, we measure a phase shift of \( (1.10 \pm 0.14) \times 10^{-5} \text{rad} \) per photon, which is in good agreement with the expected value of \( 1.0 \times 10^{-9} \text{rad per photon} \). We note that there is some uncertainty on the parameters—such as the waveguide cross-sectional area and fibre-to-waveguide coupling loss—that go into this estimate.

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. Put into the context of an interaction with a single photon in a time-bin qubit state, this implies that the measurement does not project the qubit onto a specific set of basis states and thus alter it. Towards this end, we select early and late signal modes, each of 10 ns duration, separated by 18.3 ns, and featuring a detuning of \( +100\,\text{MHz} \). Keeping the total energy constant, we generate signals in which the energy is concentrated in either the early or the late mode, or in an equal superposition \( |\Psi\rangle = (|\text{early}\rangle + |\text{late}\rangle) / \sqrt{2} \). The resulting probe phase shifts, averaged for each pulse sequence over 1,000 repetitions, are plotted in Fig. 4, 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 that 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 stored in the thulium ions that form the AFC. As illustrated in Fig. 2b, we then send a signal whose temporal structure, intensity and detuning with respect to the AFC we can vary, depending on the desired measurement. After the storage time \( t_m \), the probe pulse is re-emitted from the waveguide. To measure its phase change due to the interaction with the signal, we interfere it with a local oscillator (LO). See the ‘Methods’ section for more details about AFC generation and measurement.

First, to verify the probe-phase-shift dependence given in equation 1, we use a signal pulse in a single temporal mode of 130 ns duration. We vary the number of photons per pulse for nine different detunings, and record the phase shift of a probe pulse featuring a mean photon number of \( 1.7 \times 10^5 \), averaged over 200 repetitions, for each type of signal pulse. See Supplementary Fig. 2 for an example of the detected output with and without the signal present. As expected, we find a linear increase as a function of the number of signal photons, and that the slopes for red and blue detuning have opposite signs, as shown for two detunings in the insets of Fig. 3. From the fitted slopes we find that, within experimental uncertainty, the phase shifts are the same irrespective of the signal state, and that 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 cross-phase interaction measurement (see the ‘Methods’ section for details). As shown in the inset of Fig. 4, 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, or modifying, its state.

Discussion

While our proof-of-principle demonstration confirms the key features of the proposed scheme, a lot remains to be done before qubits encoded into individual and spectrally multiplexed photons can be detected non-destructively and without averaging. We expect that a reduction of the interaction cross section, for example, using a small-diameter ridge waveguide or structures fabricated by focused-ion-beam milling\(^46,47\), can improve the phase sensitivity by more than a factor of 100 (see equation 1). Furthermore, the ratio between the radiative lifetime \(\gamma\) and the detuning \(\Delta\) has to be increased beyond its current value of \(8.1\text{kHz}/(2\pi \times 65\text{MHz}) \approx 2 \times 10^{-5}\)—as we discuss below, this ratio can in principle approach one per cent. With these improvements, the phase shift per photon could thus be as large as 0.1 mrad, which would allow single-shot detection of individual photons\(^48\).

Reducing the detuning to maximize \(\gamma/\Delta\) comes with the unwanted effects of increasing off-resonant absorption of the signal in the AFC, increasing the noise due to decay from excited atoms, and decreasing the bandwidth of the signal. However, as we discuss in more detail in Supplementary Note 1, these problems can be overcome in a configuration in which the population in the excited state (populated through the absorption of the strong probe in the AFC) is temporarily transferred to an auxiliary level, and in which the signal passes many times through the spectral pit during the storage of the probe using, for example, a cavity\(^40\). This makes it possible to increase the detuning and thus reduce the absorption of the signal without decreasing the number of atoms in the AFC nor the total phase shift experienced by the probe. For instance, we anticipate the non-destructive measurement to be feasible using an AFC with teeth of optical depth 30 (ref. 37) and signal photons of half a MHz bandwidth that interact \(\approx 900\) times with the stored probe, which corresponds to the use of a moderate-finesse cavity (see Supplementary Note 1 for details).

We emphasize that the cross-phase interaction in rare-earth-ion-doped crystals is straightforward to generalize to multiple spectral channels, as demonstrated in the context of AFC-based optical quantum memory\(^41\), which can extend over a total bandwidth of hundreds of GHz\(^49\). We also note that the present approach should allow the development of a standard
improved laser locking. In addition, pulse intensity fluctuations and electronic noise of the photodetector contribute ~50 mrad of phase uncertainty. By averaging phases over 5 measurement repetitions, the sensitivity improves by a factor of $j^{-1/2}$. For instance, for $j = 200$, we reach a resolution of ~$7$ mrad.

**Qubit measurements.** The variation of the signal due to the interaction with the probe is assessed as follows: for early and late signal states we measure the pulse heights in the wrong time bin, normalized to the sum of the pulse heights in both bins. For the superposition states, we pass the signal through an imbalanced fiber interferometer whose arm-length difference corresponds to 18.3 ns travel-time difference. Using a piezoelectric transducer in one arm of the interferometer, we set its phase to obtain maximum constructive interference in one output, and record the normalized pulse heights in the other (the wrong) output. All measurements are repeated twice—once before, and once after the signal is submitted to the cross-phase interaction. Differences in the results indicate the perturbation of the signal due to the measurement.

**Data availability.** The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information.

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Author contributions
The scheme was conceived by C.S. with input from W.T. and the theory developed by K.H. and C.S. The experiment was developed and performed, and the data analyzed by N.S., C.D. and D.O. with guidance from W.T. All authors contributed to discussing the data and writing the manuscript.

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