Photon hole nondemolition measurement scheme by electromagnetically induced transparency

Serge Rosenblum, Alex Hayat, Pavel Ginzburg, David Neiman, and Meir Orenstein
Department of Electrical Engineering, Technion, Haifa IL-32000, Israel

(Received 21 January 2010; published 24 May 2010)

We propose a scheme for quantum nondemolition measurement of photon holes based on electromagnetically induced transparency, which allows direct nondestructive detection of the photon holes. We analyze a scheme based on interaction of a photon hole signal and a coherent probe field with a three-level atomic medium. Using recent advances in electromagnetically induced transparency technology, we show that the measurement is nondestructive for very weak photon hole signals.

DOI: 10.1103/PhysRevA.81.053848 PACS number(s): 42.50.Gy, 32.80.−t

I. INTRODUCTION

Nondestructive measurement of a physical system requires that successive measurements of the observable of interest yield identical outcomes. When this requirement is fulfilled, the measurement is called a quantum nondemolition (QND) measurement [1,2]. In such an ideal measurement, the interaction between the measurement apparatus and the system is not permitted to affect the measured state if it is initially an eigenstate of the measured observable. This essential requirement is often being taken care of by coupling the observable of interest to another system, which is then measured. QND measurements are useful in quantum optics [3–5] and in fundamental quantum physics [6]. Moreover, they may be of use in quantum computing [7], where they might contribute to nondestructive analysis of entangled photons [8,9], enabling implementation of controlled NOT gates [10].

Performing QND measurements on photonic qubits in optics is challenging, since photons are usually detected by materials that absorb the photons as they pass through them. Non-resonant effects have been used to cause dispersive phase shifts that can be detected without absorbing the signal photons. However, these effects are weak, and are thus effective only for strong fields. Successful efforts have been made to develop systems that perform QND measurements of photon number states using near-resonant interactions in high-Q cavities [11,12]. Finally, by using giant Kerr nonlinearities [13] photonic QND measurements at low light levels might be implemented in the near future.

Recently, the concept of photon holes (PHs) was introduced [14,15]. A PH is defined as the temporal decrease of the field strength in a coherent beam background. It has been suggested that PH time-bin qubits may be less susceptible to decoherence than their photonic counterparts. Time-entangled PHs were predicted to appear when two PHs are simultaneously created by irradiating a two-photon absorbing medium with two coherent beams. Quantum behavior may also emerge in single PHs, suggesting single PHs as a possible alternative to single-photon qubits. Although correlated PH generation was demonstrated experimentally, the measurements of PHs were done indirectly by photodetectors that detect the background photons.

Here we propose detecting the PHs directly in a QND measurement of the PH-signal beam, by monitoring the transmission of a probe pulse when both beams cross an atomic vapor. By coupling specific levels in the medium, the atoms can be approximated by Λ configuration three-level systems (Fig. 1). The suggested system leaves background signal photons unaffected (Fig. 2), while the presence of a PH results in a detectable delay of the probe pulse (Fig. 3), which is transmitted by electromagnetically induced transparency (EIT) [16–19]. More importantly, the PH itself is unaffected by the system, making the detection scheme nondestructive. The proposed system differs from traditional photon QND systems in that it contains collective resonant interactions, significantly increasing the light-matter coupling strength.

II. SYSTEM DYNAMICS

The dynamics of the Λ-configuration three-level medium and the beams are governed by the Maxwell-Bloch equations for three-level systems,

$$
\begin{aligned}
(\partial_{ct} + \partial_z)\,\Omega_{31} &= i\eta_1\rho_{31},\\
(\partial_{ct} + \partial_z)\,\Omega_{32} &= i\eta_2\rho_{32},\\
\dot{\rho}_{11} &= -2\mathrm{Im}\Omega_{31}^{*}\rho_{31} + 2\gamma_{31}\rho_{33},\\
\dot{\rho}_{22} &= -2\mathrm{Im}\Omega_{32}^{*}\rho_{32} + 2\gamma_{32}\rho_{33},\\
\dot{\rho}_{31} &= -i\Omega_{31}(\rho_{33}-\rho_{11}) + i\Omega_{32}\rho_{21} - (\gamma_{31}+\gamma_{32}-i\Delta_1)\rho_{31},\\
\dot{\rho}_{32} &= -i\Omega_{32}(\rho_{33}-\rho_{22}) + i\Omega_{31}\rho_{12} - (\gamma_{31}+\gamma_{32}-i\Delta_2)\rho_{32},\\
\dot{\rho}_{21} &= -i\Omega_{31}\rho_{23} + i\Omega_{32}^{*}\rho_{31} + i\delta\rho_{21},
\end{aligned}
\tag{1}
$$

where $\rho_{ij}(z,t)$ are the collective density matrix elements of the atomic medium. We defined the Raman detuning $\delta = \Delta_1 - \Delta_2$, with Δ_1,Δ_2 the detunings of the probe and signal from the corresponding atomic transitions. $2\gamma_{31}$ and $2\gamma_{32}$ are the spontaneous emission rates from state $|3\rangle$ to states $|1\rangle$ and $|2\rangle$, respectively. Pure dephasing processes and decay between the ground states are neglected. $\Omega_{3m}(z,t)$ are the Rabi frequencies, the index $m = 1,2$ denoting the probe and signal beams, respectively. $\eta_m = N\gamma_{3m}\sigma$ is the coupling between the beam and the medium, where N is the atomic density and $\sigma = 3\lambda^2/2\pi$ is the on-resonance absorption cross section, with $\lambda = \lambda_1 \approx \lambda_2$ the wavelength of the atomic transitions.

Under conditions of a weak probe pulse and zero detunings, an adiabatic solution for the probe pulse propagation can be found for the Maxwell-Bloch equations. We assume that all

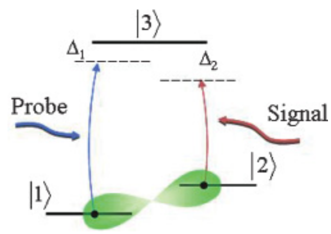

FIG. 1. (Color online) Schematic description of the irradiated three-level atom.

atoms are first pumped into state $|1\rangle$ by the signal beam. Introducing the mixing angle, defined by $\tan^2(\theta) = \eta_1 c/\Omega_{32}^2$ with c the speed of light, the dark polariton field [20,21] of the probe

$$\Psi(z,t) = \cos(\theta)\,\Omega_{31}(z,t) - \sqrt{(\eta_1 c)}\,\sin(\theta)\rho_{21}(z,t) \qquad (2)$$

solves the shape-preserving propagation equation

$$\partial_{ct}\Psi + \cos^2(\theta)\partial_z\Psi = 0. \qquad (3)$$

Hence, a dark-state polariton travels without absorption or dispersion through the dense medium with a group velocity given by $v = \Omega_{32}^2/\eta_1$ for weak fields. Pulse compression by a factor of v/c will occur upon the entrance of the probe, caused by the reduction in group velocity of the leading edge of the probe beam as it enters the EIT medium, while the tail continues to propagate at the speed of light. However, the pulse amplitude remains unchanged, since the index of refraction is unity under EIT conditions. Hence, the probe beam retains only v/c of its electromagnetic energy. The signal pulse is nearly decoupled from the medium, since electrons reside mostly in the left ground state $|1\rangle$. Therefore, the velocity of the signal will be much higher than the probe's velocity.

By turning the signal off adiabatically to generate the PH, the light is stopped [22]. In that case we have $\Psi \propto \rho_{21}$, that is, the polariton is entirely in the form of a stationary electronic superposition wave. Upon subsequent switching on of the signal, the polariton is re-emitted.

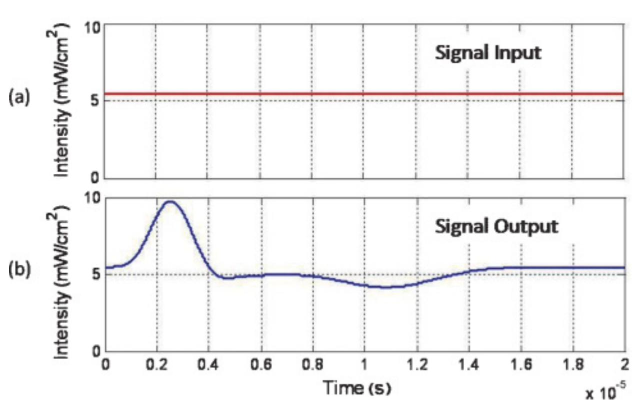

FIG. 2. (Color online) The input signal beam without PH in (a) propagates largely undisturbed through the medium, yielding the output beam (b). The increase in the signal's leading-edge amplitude is due to Raman scattering of the probe beam into the signal beam.

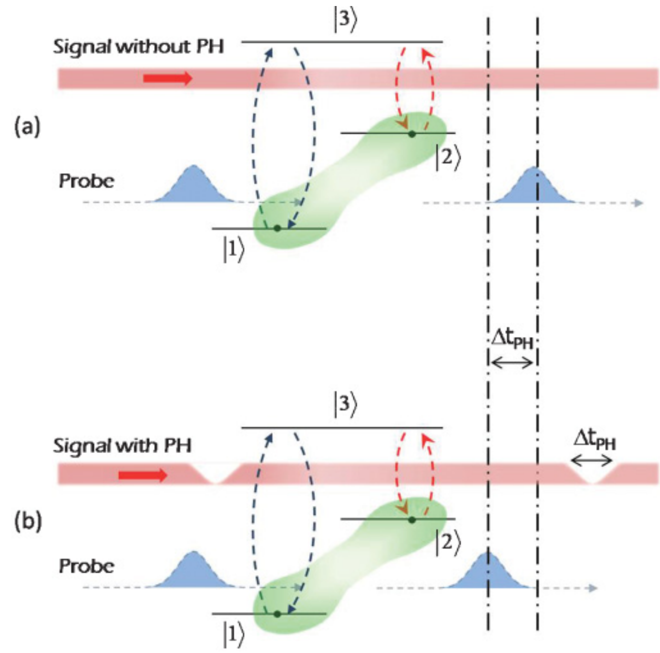

FIG. 3. (Color online) Schematic depiction of the suggested system. (a) No PH is present in the signal beam. The probe beam propagates undisturbed through the EIT medium. (b) A PH is present in the signal beam. The probe beam experiences a delay equal to the PH width.

EIT occurs only if the probe beam is contained in the spectral transparency window of width [23]

$$\Delta_{\mathrm{tr}} \sim (D_O)^{-1/2}\,\Omega_{32}^2/\gamma_{31}, \qquad (4)$$

where the optical depth $D_O = LN\sigma$, with L the medium length, is a measure of the opacity of the medium. A probe pulse satisfying the condition of Eq. (4) can be delayed to the extent of being contained entirely in the medium, only if the latter satisfies $D_O \gg 1$.

As soon as the PH enters the medium, the remaining energy of the probe beam will be scattered into the signal beam. Since by that time only a very small fraction of the polariton is electromagnetic, the resulting PH filling is negligible. The probability of PH filling is given by the ratio of the remaining electromagnetic intensity of the probe polariton to the background intensity of the signal beam I_{32}. For low signal intensities, this yields

$$P_{\mathrm{fill}} = (v/c)I_{31}/I_{32} = \Omega_{31}^2/(\eta_1 c), \qquad (5)$$

where I_{31} is the input probe intensity. P_{fill} can be estimated to be around 10^{-5} for practical parameters, and thus the measurement is indeed nondestructive.

When the PH leaves the medium, that is, the signal is switched on again, the probe polariton is re-emitted with the original group velocity. However, the polariton has been delayed by the PH width Δt_{PH}. This delay can be detected by using a photon detector sensitive to the probe beam and measuring the delay relative to the signal without PH.

III. PRACTICAL FEASIBILITY

For a vacuum PH of width Δt_{PH} to correspond to a signal background where about n_{sig} photons have been removed, the background signal intensity needs to satisfy

$$I_{32} = n_{\text{sig}} hc/(\lambda A \Delta t_{\text{PH}}), \tag{6}$$

where A is the beam cross-sectional area. The proposed experiment is not interferometric, but a regular direct photon detection experiment, and therefore the shot noise imposes a limit on the delay that can be detected. The probe delay caused by the PH can be observed only if the number of photons in the probe beam n_{pr} satisfies

$$n_{\text{pr}} > (\Delta t_{\text{pr}}/\Delta t_{\text{PH}})^2, \tag{7}$$

where Δt_{pr} is the probe width. By combining Eqs. (6) and (7), we obtain

$$I_{31} > I_{32}(\Delta t_{\text{pr}}/n_{\text{sig}}\Delta t_{\text{PH}}). \tag{8}$$

If we assume equal oscillator strengths for both transitions, we cannot take the probe beam to be stronger than the signal beam, since adiabatonic effects [24] would become too pronounced. These would cause significant spreading of the probe beam and a large dip in the signal beam. Therefore, by Eq. (8), to achieve noticeable delays we need a probe width comparable to the PH width $\Delta t_{\text{pr}} < n_{\text{sig}}\Delta t_{\text{PH}}$. On the other hand, the initial probe spectrum needs to be contained inside the transparency window; hence, the probe width should satisfy

$$\Delta t_{\text{pr}} > n_{\text{sig}}^{-1}\sqrt{D_O}(A/\lambda^2)\Delta t_{\text{PH}}, \tag{9}$$

where we used the identity $\Omega_{32}^2 = \gamma_{32}\sigma\lambda I_{32}/(hc)$. Thus, the pulse area has to be comparable in size to the cross section $A \propto \lambda^2$. This can be achieved by using hollow-core photonic

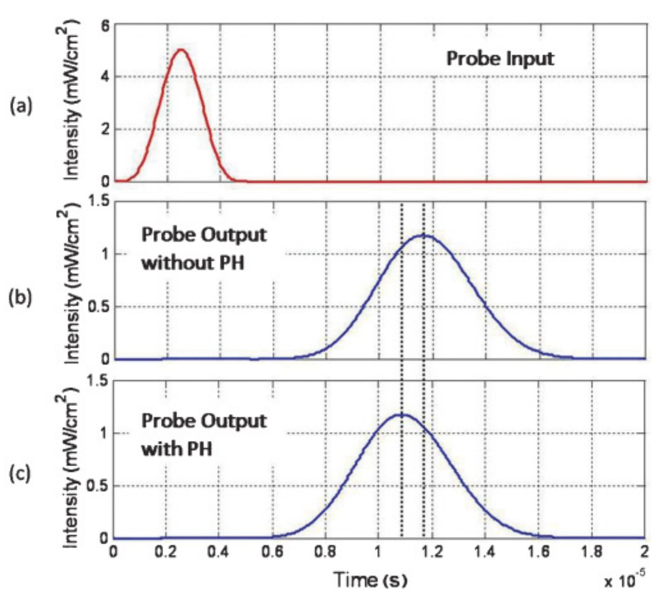

FIG. 4. (Color online) Simulation of the probe delay. The input in (a) propagates through the medium. In (b) the output of the probe is shown when no PH is present in the signal. In (c) there is a delay as a result of the presence of a PH in the signal.

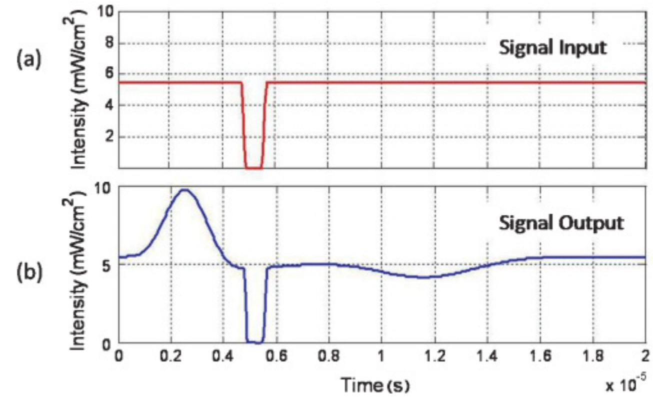

FIG. 5. (Color online) The signal beam with PH at the input (a) remains unaffected after propagation through the medium (b), except for some initial Raman scattering. This increase in the leading-edge amplitude occurs independently of the presence of a PH, and can thus be deterministically removed.

bandgap fibers [25,26] instead of traditional vapor cells. Moreover, the number of photon absences in a PH is bounded by

$$n_{\text{sig}}^2 > \sqrt{D_O}(A/\lambda^2). \tag{10}$$

A possible realization of the proposed system may employ a hollow-core fiber filled with ^{87}Rb atoms whose $5S_{1/2}$-to-$5P_{1/2}$ transition with signal wavelength 795 nm is often used for EIT. The atomic density is chosen to be 10^{11} cm^{-3} to obtain an optical depth of $\sim$3000 for a $\sim$10-cm-long fiber. We take the average photon number in the signal background to be $\sim$100 photons per 0.5 μs, in order for a PH pulse of width 0.5 μs to be the absence of 100 photons. Taking a probe beam of equal amplitude to the signal, the corresponding intensities for the signal and probe beams are $\sim$5 mW/cm^2 for a beam confinement to an area of $\sim$1 μm^2. The minimal probe width is then given according to Eq. (9) by $\Delta t_{\text{pr}} > 1$ μs. Thus, by choosing a probe width of 5 μs a delay of 10% can be achieved (Fig. 4) without affecting the PH (Fig. 5).

IV. CONCLUSION

In conclusion, we propose QND measurements of a signal beam in which the information is encoded in PHs, which are temporal dips in the electric field amplitude. This is done by passing the signal and probe beams through a hollow-core fiber containing a thick vapor of Λ-configuration three-level atoms. If the signal does not contain a PH, the probe passes the medium without any absorption or dispersion. However, if there is PH in the signal, the probe is completely absorbed. When the signal beam is switched on again, the probe beam is re-emitted. The resulting delay can be observed, making possible the conclusion that a PH was present in the signal beam. However, the signal beam is not affected by the medium. Hence, a PH nondemolition measurement is performed. Because of the strong resonant coupling and the collective interactions in EIT, PHs in very weak backgrounds can be detected. The lower bound on the background intensity is given by $n_{\text{sig}}^2 > \sqrt{D_O}(A/\lambda^2)$, corresponding to tens of photons per time bin.

ACKNOWLEDGMENTS

We thank O. Firstenberg for fruitful discussions. A.H. is supported by the Adams Fellowship Program of the Israel Academy of Sciences and Humanities.

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