Electromagnetically Induced Transparency in Cesium Vapor with Probe Pulses on the Single-Photon Level

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We perform electromagnetically induced transparency (EIT) experiments in cesium vapor with pulses on the single-photon level for the first time. This was made possible by an extremely large total suppression of the EIT coupling beam by 118 dB mainly due to a newly developed triple-pass planar Fabry-Pérot etalon filter. Slowing and shaping of single-photon light pulses as well as the generation of pulses suitable for quantum key distribution applications and testing of approaches for single photon storage is demonstrated. Our results extend single-photon EIT to the particularly interesting wavelength of the Cs $D1$ line.

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Coherent interaction between photons and atomic ensembles has attracted much attention over the past decade. Research is motivated on one hand by quantum information processing where the ability to map quantum states between light and matter is crucial. Proposals and first demonstrations concerned quantum memories as fundamental building blocks for quantum repeaters [1] and photon storage for more advanced quantum networks [2]. Moreover, deterministic sources for single photons and entangled photon pairs needed in linear optics quantum computing [3] were proposed and demonstrated [1,4]. On the other hand, tailoring the optical properties of matter by coherent preparation establishes very long optical delay lines [5] and tremendously enhances nonlinear coefficients [6].

Most of the experiments demonstrated so far utilize a Λ-type level scheme in alkali atoms. Typically, a weak probe beam is sent into an ensemble which is optically pumped by a much stronger coupling beam. If both probe and coupling beam are off resonant, a coherent Raman transition is introduced if the two-photon resonance condition is met. In a condition where probe and coupling beam are nearly resonant, the phenomenon of electromagnetically induced transparency (EIT) is observed. Since its first demonstration in 1991 by Boller *et al.* [7], EIT has attracted much attention, and its capability to slow down [5] and even stop light [8] was shown. EIT-based setups for light storage in atomic vapor at room temperature were first demonstrated in 2001 [9]. In the meantime, even single photons have been stored in such setups [10]. EIT can also be utilized for all-optical control of amplitude and phase of a light pulse down to the single-photon level. Such a control facilitates loading of a single photon into an optical cavity in quantum interfaces [11] or their storage in an atomic ensemble [12]. Cross-phase modulation on the single-photon level mediated by EIT [13,14] is important for establishing optical quantum gates [15]. Both regimes can be described within a common theoretical framework applicable for any Λ-type system [16]. However, most of the experiments in atomic vapor so far have used rubidium atoms [9,12]. Cesium, however, offers certain advantages, e.g., the $F = 3 \rightarrow F = 4$ hyperfine ground state clock transition, allowing the realization of all-optical atomic clocks [17]. The ^{133}Cs $D1$ line at 894 nm lies well within the wavelength regime of exciton emission from InAs quantum dots [18], which is relevant for possible coherent interfaces between atomic and solid-state systems [19].

Very recently, Reim *et al.* [20] demonstrated coherent storage and retrieval of subnanosecond low-intensity (several thousand photons) light pulses with spectral bandwidths exceeding 1 GHz utilizing a far off resonant two-photon Raman transition. In this experiment cesium offered the advantage of smaller Doppler linewidth, i.e., $\sim$380 MHz in ^{133}Cs compared to $\sim$540 MHz in ^{87}Rb at room temperature, and larger hyperfine splitting of 9.2 and 6.8 GHz, respectively. The latter sets a limit to the maximum storage bandwidth. In spite of the potential advantages, there have been no experiments on the single-photon level with cesium vapor, for the most part because of the problem to filter the strong coupling beam. In this Letter, we overcome this problem and demonstrate for the first time EIT with pulses at the single-photon level.

In order to map quantum states of light on atomic ensembles, photons with a spectral width on the order of Doppler-free atomic lines (a few MHz) are required. Although such kind of narrow band photon sources have been demonstrated recently using cavity-enhanced parametric down-conversion [21], we mimic single photons with highly attenuated laser pulses from a diode laser in this experiment. In this way the pulse length and thus the spectral bandwidth can be controlled conveniently by an electro-optic modulator (EOM). The experimental setup is sketched in Fig. 1(a). EIT is performed within the $D1$ transition of ^{133}Cs in a Λ-shaped atomic system as shown in Fig. 1(b). Two extended-cavity diode lasers around 894 nm are used as probe and coupling laser. The probe laser is stabilized to the $6^2S_{1/2}(F = 3) \rightarrow 6^2P_{1/2}(F' = 4)$

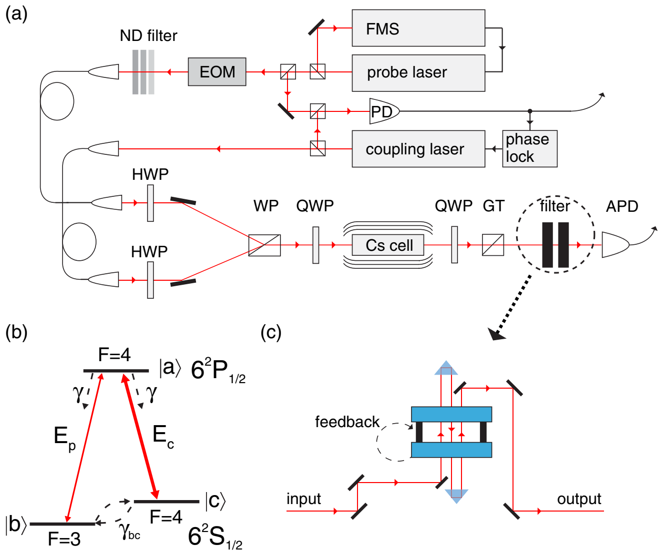

FIG. 1 (color online). (a) Experimental setup consisting of probe and coupling laser, frequency modulation spectroscopy setup (FMS), an electro-optical modulator (EOM), Wollaston prism (WP), polarization optics, i.e., half-wave plate (HWP), quarter-wave plate (QWP), and polarizing beam splitter, as well as a Glan-Thompson prism (GT) and spectral filtering (see text). A photodiode (PD) and avalanche photodiode (APD) are used for detection. (b) Λ-type atomic level scheme implemented in Cs. E_p is the probe field, E_c is the coupling field. (c) Details of the multipass Fabry-Pérot etalon used for spectral filtering of the coupling beam. Two retroreflectors above and below the etalon direct the light beam at different positions three times through the instrument. The substrates are connected by three piezoelements, and a closed-loop controller together with strain gauge sensors in each piezoelement controls the mirror distance.

hyperfine transition by Doppler-free frequency modulation spectroscopy. The coupling laser is frequency offset-locked to the probe laser using an optical phase-locked loop with the appropriate frequency offset of $\approx$9.2 GHz [22]. It is resonant with the $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{1/2}$ $(F' = 4)$ transition. The probe laser can be amplitude modulated by an EOM driven by an arbitrary waveform generator and is strongly attenuated by several neutral density (ND) filters. The electronics and EOM transfer function were measured and the driving waveform shaped in such a way to produce perfectly Gauss-shaped probe laser pulses.

A vapor cell of 4 cm length filled with isotopically pure ^{133}Cs without buffer gas and temperature stabilized at around 26 °C is used as EIT medium. It is magnetically shielded using three layers of μ metal. In front of the cell, coupling and probe laser are orthogonally linearly polarized and superimposed by a Wollaston prism. The polarization is changed to left and right circular, respectively, and both lasers copropagate through the Cs cell. The beam waist of the probe beam and the coupling beam is 1 and 4.5 mm, respectively. Behind the cell, the polarization is transformed back to linear and a Glan-Thompson prism (GT) filters the coupling beam. To allow detection of the probe pulses on the single-photon level while using a coupling laser power of 1.2 mW, the coupling laser needs to be further suppressed in front of the detector. This is achieved by spatial filtering with a single-mode fiber (not shown in the figure) and a triple-pass planar Fabry-Pérot etalon (FP) [23]. Behind all filters a single photon counting avalanche photodiode is used for detection. The combined filter transmission and detection efficiency is 10% for the probe photons. It is the extremely large total suppression of the coupling beam by 118 dB, i.e., 108 dB signal-to-noise ratio, which makes single-photon experiments possible. To achieve this suppression, a great deal of effort had to be put into the FP filter shown in Fig. 1(c). It alone accounts for 46 dB coupling beam suppression while it has a peak transmission of 65% for the probe beam. It was built from substrates matched to $\lambda/280$ which are connected by three piezoelements. A closed-loop controller together with strain gauge sensors in each piezoelement controls the mirror distance and parallelism with nanometer precision allowing us to remove virtually all mirror tilt and simultaneously tune the instrument's transmission wavelength.

For the first measurements we used attenuated probe pulses at a rate of 100–200 kHz with a mean photon number $\bar{n} = 1.0 \pm 0.1$. The detector counts were integrated for up to 30 min in order to increase the signal-to-noise ratio. A constant non-time-correlated background of 20 000 counts per second was measured and thus subtracted in the analysis. The noise signal was further studied by scanning the FP filter around the probe transition wavelength when only the coupling laser was applied and the measurement was simulated by a Voigt profile with the FP linewidth as FWHM for the Lorenzian part [24] and the FWHM of the Gaussian part as fit parameter. As shown in Fig. 2, the peak width is largely defined by the width of the FP filter, the Gaussian FWHM is found to be only 47 MHz, which suggests a narrow band noise source. Accordingly, the most dominant noise source is anti-Stokes Raman scattering into the probe mode. The noise was found to increase both with cell temperature and coupling field intensity.

The Cs cell is movable perpendicular to the laser propagation between two fixed positions. This allows measurements of probe pulse delays with and without the cell. Compared to the measurement of off resonance transmission through the cell, as it is often performed in other experiments, this method does not require any other change in the experimental configuration. In this way, the laser lock and Fabry-Pérot configuration is unaffected, making the procedure more reliable.

In a first experiment, the delay of a pulse at the single-photon level caused by the low group velocity inside the Cs cell was studied. The delay times were measured by fitting a Gauss curve to the temporal distribution of the probe photon detection events with and without the EIT cell in the beam

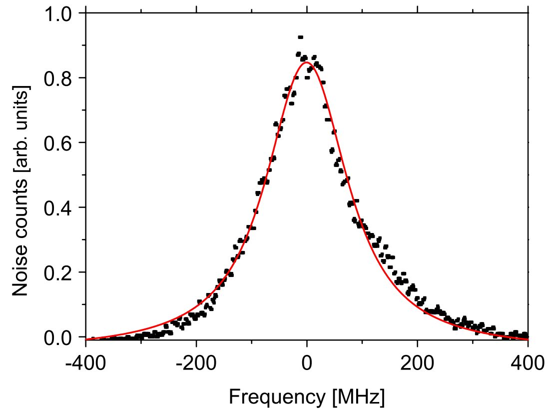

FIG. 2 (color online). Scan of the FP filter around the probe transition wavelength (black points). The simulation [gray (red) line] is performed using a Voigt profile with the FP linewidth as FWHM for the Lorenzian part; the Gaussian FWHM as fit parameter is found to be 47 MHz.

line. Figure 3(a) shows a measurement for a probe pulse length of ≈1.5 μs. A transmission of 25% for the probe pulse can be derived. Subsequently, we performed a systematic study of EIT delays for varying lengths of the probe pulses [Fig. 3(b)]. The intensity of the probe pulses was adjusted in order to maintain the average intensity of one photon per pulse. A comparison of the delayed pulse [gray (blue) curve in Fig. 3(a)] versus the undelayed pulse [black curve in Fig. 3(a)] reveals an additional modification of the pulse shape. This is due to group velocity dispersion since the spectral width of the probe pulses (ranging from 100 kHz to 4.5 MHz) may exceed the EIT transmission window which is around 720 kHz in our experiment.

The measured data are compared to a theoretical analysis treating EIT in room temperature gas cells, e.g., Ref. [25]. From the density matrix formalism and in the case of a weak probe field the susceptibility can be calculated. A convolution with the velocity distribution of the atoms in the EIT cell accounts for Doppler broadening. From the susceptibility the index of refraction and thereby the speed of light inside the cell and the pulse delay can be calculated. Figure 3(b) shows the theoretical curve using experimentally accessible parameters, e.g., cell temperature, spontaneous emission rate of the Cs $D1$ line, and coupling laser power. The atomic dephasing rates were introduced as the only fit parameter. An excellent agreement with the measured data [dots in Fig. 3(b)] is observed even for pulses with a width exceeding the EIT transparency window.

The successful demonstration of EIT in the Cs cell at ultralow intensity then allowed coherent amplitude and phase control of light pulses on the single-photon level [10]. We used an acousto-optic modulator (AOM) [not shown in Fig. 1(a)] which modulates the coupling laser's amplitude. The AOM was controlled by a second arbitrary waveform generator triggered simultaneously with the EOM controller. In this way an arbitrary waveform of the probe pulse can be generated. As an example, Fig. 4 shows a pulse at the single-photon level which was split into two pulses. Such a waveform represents a time-bin encoded state [26] since the phase between the two components of the wave packet can be controlled by changing the off-time duration of the coupling laser. On the other hand, the EIT cell can be regarded here as a temporal beam splitter capable to distribute a pulse at the single-photon level over two distinct temporal modes. In conjunction with "true" narrow band single photons [21], a so-called "single-photon entangled state" can be generated and subsequently transferred to other atomic ensembles, as discussed and demonstrated by Choi *et al.* [27]. In the EIT cell an amplitude modulation of the strong coupling field is transferred to the weak, possibly single-photon field. This may be exploited to a transfer of quantum correlations between quadrature components of two strong

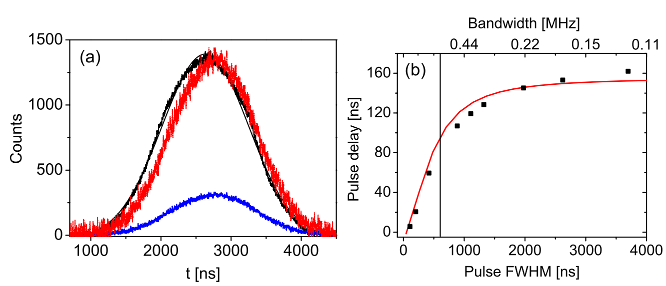

FIG. 3 (color online). (a) Delayed single-photon probe pulse. The black [gray (blue)] line shows the pulse without (with) EIT cell. For comparison the curve for the delayed pulse is multiplied by a factor of 4 and plotted as thick gray (red) curve. (b) Dependence of time delays on the FWHM spectral and temporal width of the probe pulse. The vertical bar indicates the width of the EIT transmission window. The dots are experimental results, and the solid line is a theoretical calculation (see text).

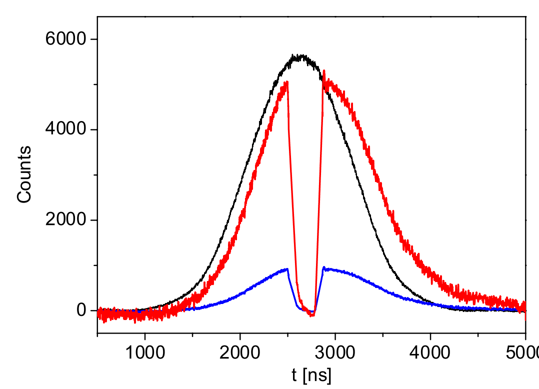

FIG. 4 (color online). Control of a single-photon wave packet by modulation of the coupling laser. The black curve is the undisturbed pulse without EIT cell. The lower gray (blue) curve shows the probe pulse which is split coherently into two components thus forming a time-bin encoded state on the single-photon level. For comparison the curve for the split pulse is multiplied by a factor of 5.5 and plotted as thick gray (red) curve.

beams to correlations between a quadrature component of a strong beam and the phase of a single photon. An example would be to use one arm of two macroscopically entangled (squeezed) beams as coupling laser in an EIT configuration and to map, e.g., its amplitude fluctuation on the phase of a single photon. Such a beam could be produced by an optical parametric amplifier (OPA) [28]. Preliminary studies in a modification of our setup (using one arm of a Mach-Zehnder interferometer as probe beam) show that such a cross-phase modulation between coupling and weak probe laser [13] is indeed possible.

In conclusion, we performed slowing and shaping of single-photon light pulses using EIT in Cs vapor for the first time. We demonstrated that time-bin encoded states on the single-photon level can be generated and controlled with wavelengths corresponding to the Cs $D1$ line. Experiments with "true" single photons generated by cavity-enhanced parametric down-conversion [21] can be envisioned. Our results extend single-photon EIT to a particularly interesting wavelength. For example, in conjunction with recently demonstrated broadband optical quantum memories in Cs vapor cells [20], manipulation or storage of single or entangled photons from semiconductor sources at a wavelength capable to match Cs transitions [29] becomes feasible. This could be a first step towards a possible interface between semiconductor quantum dots and atomic ensembles. Operating a broadband memory on the single-photon level would be attractive for several reasons: It would require less effort on the side of the single-photon source as photons need not be as narrow band as for an EIT-based storage system. Also it might overcome the problems of Raman noise which, as our measurements suggest, are still an obstacle even with improved noise suppression. Finally, based on very recent works [30] regarding so-called spread spectrum technology at the single-photon level, it might allow us to build a memory to store spread spectrum encoded ultranarrow band single photons. Using two synchronously driven electro-optic phase modulators as transmitter and receiver, a narrow band photon might be modulated and thus broadened for storage and later demodulated for detection behind a narrow band filter. This should further reduce the problem of noise photons and eventually lead to multiplexing of single photons inside the memory, i.e., multimode quantum memories.

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