Efficiently Loading a Single Photon into a Single-Sided Fabry-Perot Cavity

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We demonstrate that a single photon with an optimal temporal waveform can be efficiently loaded into a cavity. Using heralded narrow-band single photons with exponential growth wave packet shaped by an electro-optical amplitude modulator, whose time constant matches the photon lifetime in the cavity, we demonstrate a loading efficiency of $(87 \pm 2)\%$ from free space to a single-sided Fabry-Perot cavity. We further demonstrate directly loading heralded single Stokes photons into the cavity with an efficiency of $(60 \pm 5)\%$ without the electro-optical amplitude modulator and verify the time reversal between the frequency-entangled paired photons. Our result and approach may enable promising applications in realizing large-scale quantum networks based on cavity quantum electrodynamics.

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Light confined in a small cavity can behave significantly different from that in free space. It has now become possible to control the quantum mechanical interaction between a single photon and a single atom inside a reflective cavity [1,2]. The local cavity nodes can be remotely linked by flying photonic quantum bits to form a quantum network, which opens wide applications for quantum computation, communication, and metrology [3–5]. The connectivity and scalability of such a cavity quantum electrodynamics based quantum network strongly depends on the efficiency of loading a single photon from free space into the cavity. However, in most experimental demonstrations with photons injected from free space, the photon-cavity loading efficiency is low ($< 20\%$) [5–12].

When a free-space photon meets a nonabsorptive cavity, its wave packet is usually divided into three parts: reflected, loaded inside the cavity, and transmitted. If the wave packet is too short and its spectrum is much wider than the cavity resonance, the incident photon is most likely reflected by the front mirror without entering the cavity. If the wave packet is too long, part of the wave packet leaks out before the entire wave packet enters into the cavity. Therefore, to completely load a photon into a cavity, one would expect no reflection and transmission from the cavity during the loading process. A possible solution is to make use of the time reversal symmetry between the loading and unloading processes, analog to the absorption and emission in an atomic system [13–15]. Recently it was shown that a weak classical coherent-state pulse with a time-reversed exponential growth shape can be coupled efficiently into an optical or microwave resonator [16–18], but the demonstration of loading a single photon with nearly unity efficiency remains a challenge.

In this Letter, we demonstrate that a single photon can be loaded into a single-sided Fabry-Perot cavity efficiently. Making use of heralded single photons with an exponential growth waveform shaped by an electro-optical amplitude modulator (EOAM), we demonstrate an optimal loading efficiency of about $(87 \pm 2)\%$. We further make use of a time reversal operation to demonstrate a direct loading efficiency of $(60 \pm 5)\%$ without the EOAM. The result paves the way towards the perfect excitation of a single quantum absorber inside a cavity by a true single photon [19,20].

The schematics of a single-sided cavity is illustrated in Fig. 1(a). It consists of two lossless mirrors M_1 and M_2 separated by a distance of L, whose amplitude reflectivities are r_1 and r_2, respectively. We start our model from an ideal single-sided cavity, i.e., $r_2 = 1$. A single photon with a wave packet $\Psi_{\text{in}}(z,t) = \psi_{\text{in}}(t - z/c)e^{i(kz-\omega_0 t)}$ is incident from the left side toward M_1, where c is the speed of light in vacuum, ω_0 is the cavity resonance frequency, and $k = \omega_0/c$. On M_1, because of the wave nature of the photon, its transmitted packet, after each round trip inside the cavity, interfaces with the reflected packet. If the interference is destructive such that there is no reflection from the cavity during the loading process, the photon can be loaded into the cavity completely. As shown in the Supplemental Material [21], this interference at $z = 0$ requires $\psi_{\text{in}}(t + 2L/c) = \psi_{\text{in}}(t)/r_1$, which gives the solution

$$\psi_{\text{in}}(t) = a_0 e^{\gamma_c t}\theta(-t) \tag{1}$$

as an exponential growth waveform. Here a_0 is an normalization factor, $\gamma_c = -(c/2L)\ln r_1 \simeq (c/2L)(1 - r_1/r_1)$, and $\theta(-t)$ is the heaviside function.

The cavity transfer function around the resonance frequency ($\Delta\omega = \omega - \omega_0 \ll \pi c/L$) is

$$H(\Delta\omega) \simeq -e^{i2\Delta\omega L/c}\frac{\Delta\omega - i\gamma_c}{\Delta\omega + i\gamma_c}. \tag{2}$$

The cavity lifetime is determined by $1/\gamma_c$. With the exponential growth waveform in Eq. (1), we obtain the cavity output

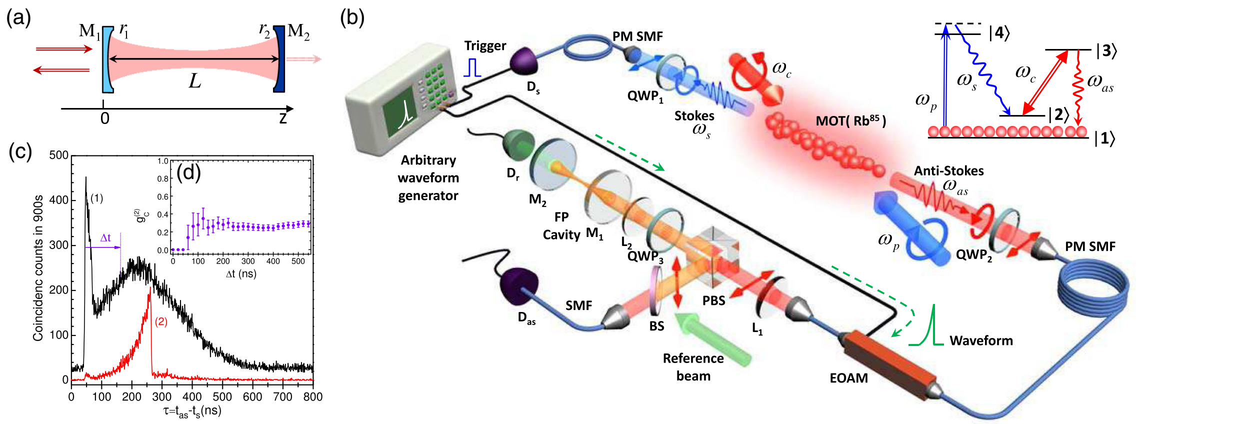

FIG. 1 (color online). Generating and loading heralded single photons into a cavity. (a) The single-sided Fabry-Perot cavity: $r_1 = 0.9955$, $r_2 = 0.9998$, and $L = 4.625$ cm. (b) Experimental setup. The anti-Stokes photons are modulated by an EOAM triggered by the detection of Stokes photons at the detector D_s. (c) Temporal waveforms of heralded anti-Stokes photons measured as a two-photon coincidence between D_s and D_{as}. Plot (1) is the waveform without modulation. Plot (2) shows the modulated exponential growth waveform. (d) $g_c^{(2)}$ of the heralded single anti-Stokes photons in plot (1) [panel (c)] as a function of coincidence window width.

$$\psi_{\text{out}}(t) = -a_0 e^{-\gamma_c(t-2L/c)}\theta(t-2L/c), \tag{3}$$

which is the time reversal (delayed by $2L/c$) of the input waveform. Note that the output is nonzero only after the loading process is completed [$\psi_{\text{out}}(t<0)=0$]. This result is consistent with the interference picture described previously in the time-space domain. Because the cavity has a finite lifetime $1/\gamma_c$, the photon will eventually leave away from the cavity with an exponential decay waveform ($t>0$). In such an ideal cavity, the loading efficiency can be 100%.

In reality, however, it is impossible to have mirror M_2 be totally reflective. As we take into account this fact ($r_1 < r_2 < 1$), the cavity transfer function becomes

$$H(\Delta\omega) \simeq -\frac{e^{i2\Delta\omega L/c}}{r_2}\frac{\Delta\omega - i\gamma_1}{\Delta\omega + i\gamma_c}, \tag{4}$$

where $\gamma_1 = (c/2L)(r_2 - r_1/r_1)$ and $\gamma_c = (c/2L)(1 - r_1 r_2/r_1 r_2)$. We define the loading efficiency as the probability of finding the photon inside the cavity at the time when the loading process is completed. Because escaping from the rear mirror M_2 is neglectable, the loading efficiency can be estimated as the output probability from the front mirror M_1 after the loading process ($t>0$). With the optimal waveform in Eq. (1), the photon loading efficiency becomes $\eta_o = (\gamma_1 + \gamma_c)^2/(4r_2^2\gamma_c^2) < 1$. The cavity used in the experiment has a free spectral range (FSR $= \pi c/L$) of 3241 MHz, $\gamma_c = 2\pi \times 2.44$ MHz, and $\gamma_1 = 2\pi \times 2.23$ MHz. The cavity round-trip time, $2L/c = 0.31$ ns, is much shorter than the time-bin width (1 ns), so from now on we neglect this delay in Eq. (3).

Our experimental setup is illustrated in Fig. 1(b). We produce counterpropagating narrow-band photon pairs using spontaneous four-wave mixing in laser-cooled ^{85}Rb atoms [22–25]. Horizontally polarized Stokes (ω_s, 780 nm) and anti-Stokes (ω_{as}, 795 nm) photons are coupled into two opposing polarization maintaining single mode fibers. The detection of a Stokes photon at the single-photon counting module (SPCM, PerkinElmer, SPCM-AQ4C) D_s sets the time origin of its paired anti-Stokes photon. The heralded single anti-Stokes photon then passes through a fiber coupled EOAM (EOSpace) which is controlled by an arbitrary waveform generator (Tektronix AFG3252) triggered by the detection of Stokes photons. After two lens (L_1 and L_2) and a polarization beam splitter, anti-Stokes photons are mode matched into a single-sided Fabry-Perot cavity. We insert QWP3 such that the anti-Stokes photons from the cavity output are vertically polarized and totally reflected by the polarization beam splitter. The anti-Stokes photons are finally detected by a second SPCM D_{as}. To lock the cavity, a reference laser is coupled into the cavity through a beam splitter (1∶9) and its transmission through mirror M_2 is monitored by D_r.

We first characterize the photon source before loading into the cavity. We connect the detector D_{as} directly to the output of the EOAM. We operate the system with an atomic optic depth (OD) of 75 on the anti-Stokes transition, a pump (ω_p, 780 nm) laser power of 15 μW, and a coupling (ω_c, 795 nm) laser power of 0.85 mW. Both pump and coupling lasers have the same beam diameter of 1.6 mm. Figure 1(c) displays the heralded anti-Stokes temporal waveform as coincidence counts collected over $T =$ 900 s with time-bin width $\Delta t_{\text{bin}} = 1$ ns. Plot (1) is obtained by fully opening the EOAM without modulation. With a joint-detection efficiency (including all loss) $\beta = 3.3\%$ and duty cycle $\zeta = 10\%$, the coincidence counts can be calculated from $C(\tau) = \beta\zeta|\psi(\tau)|^2\Delta t_{\text{bin}}T$. The spikelike oscillatory structure in the leading edge is the optical precursor contributed from far-off anti-Stokes resonance

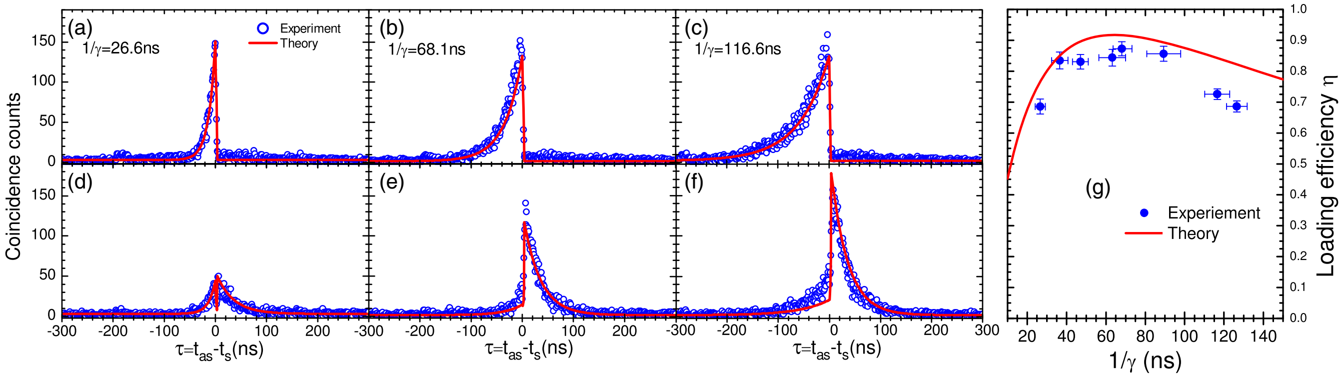

FIG. 2 (color online). Loading a single photon into a cavity with exponential growth waveforms. Panels (a)—(c) are the input single-photon exponential growth waveforms with different time constants $(1/\gamma)$. Panels (d)—(f) are the corresponding cavity outputs. The coincidence counts are collected for 1800 s. (g) Loading efficiency η as a function of the characteristic time $1/\gamma$.

frequency components [26]. We confirm the single-photon particle quantum nature of the heralded anti-Stokes photons by measuring its conditional autocorrelation function $g_c^{(2)}$ [27]. A two-photon Fock state gives $g_c^{(2)} = 0.5$. As shown in Fig. 1(d), $g_c^{(2)} < 0.5$ holds well within the entire temporal waveform and indicates the near single-photon character.

The long temporal coherence time of more than 400 ns allows us to shape the heralded anti-Stokes photon waveform using the EOAM [28], such as the example plot (2) of Fig. 1(c). Figures 2(a)—(c) are input exponential growth waveforms, with a fall time of about 3 ns at the falling edge, which is limited by the speed of the waveform generator. Figures 2(d)—(f) are the corresponding cavity outputs. When the photon is temporally short $[1/\gamma < 1/\gamma_c$, Fig. 2(a)], part of the wave packet is directly reflected from the cavity during the loading process [$\tau < 0$, Fig. 2(d)]. The optimal input is shown in Fig. 2(b), with a time constant $1/\gamma = 68.1$ ns $\simeq 1/\gamma_c = 65.4$ ns. Figure 2(e) is the output waveform as the time reversal of the input. In this case, the reflection and leakage from the cavity during the loading process ($\tau < 0$) is minimized. The finite exponential growth part during $\tau < 0$ is mainly from the modulated incoherent counts. As we further increase the temporal length of the input photon waveform [Fig. 2(c)], the loaded wave packet starts to leak out before the loading process is completed. The theoretical curves are calculated from the cavity transfer function in Eq. (4) by accounting for the incoherent counts.

We determine the experimental loading efficiency from

$$\eta_{\mathrm{exp}} = \frac{\int_0^\infty [C_{\mathrm{out}}(\tau) - C_n(\tau)]d\tau}{\int_{-\infty}^0 [C_{\mathrm{in}}(\tau) - C_n(\tau)]d\tau}, \quad (5)$$

where $C_{\mathrm{in}}(\tau)$ and $C_{\mathrm{out}}(\tau)$ are measured input and output coincidence counts. $C_n(\tau)$ are the incoherent coincidence counts. Figure 2(g) shows the loading efficiency as a function of the loading time constant. The experimental values are slightly lower than the theory because of the 3-ns fall time at the waveform falling edge. For longer $1/\gamma$, this difference becomes more substantial due to the inclusion of the precursor that is not storable [26]. The experimental optimal loading efficiency is $(87 \pm 2)\%$. The measured $g_c^{(2)}$ are 0.23 ± 0.17 and 0.30 ± 0.21, for the input waveform in Fig. 2(b) and output waveform in Fig. 2(e), respectively. Thus, the single-photon quantum nature is preserved during the loading-releasing process.

For comparison, we study loading single photons with nonexponential growth waveforms, as summarized in Fig. 3. In all these cases, the substantial temporal overlap between the input and output waveforms indicates a significant probability for the photon leaking out of the cavity during the loading process.

In the above proof-of-principle demonstration, the optimal waveform is obtained by the EOAM, whose amplitude

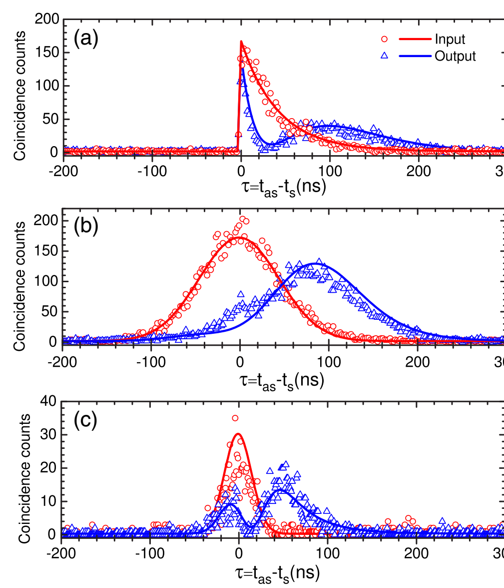

FIG. 3 (color online). Loading single photons with nonexponential growth waveforms: (a) An exponential decay waveform with a time constant matching the cavity lifetime, (b) a long Gaussian waveform, and (c) a short Gaussian waveform.

modulation leads to unavoidable loss to the single photons. To overcome this problem, here we directly produce heralded single photons with a waveform close to the optimal in a time reversal process without using the EOAM. As shown in plot (1) of Fig. 1(c), the two-photon correlation function without modulation displays an exponential decay on its tail. By adjusting the EIT parameters, it is possible to directly produce heralded anti-Stokes photons with a controllable waveform $\psi_{as,\text{in}}(t_{as}-t_s)=\psi_0(\tau)$ whose decay time approaches the cavity lifetime. In the time reversal process, if we take the anti-Stokes photon as the trigger, the heralded Stokes photon will have an exponential growth waveform $\psi_{s,\text{in}}(t_s-t_{as})=\psi_0(-\tau)$ optimized for cavity loading.

To demonstrate the direct loading, we remove the EOAM and arbitrary waveform generator. In this experiment, to shorten the biphoton temporal length and make the waveform approach the optimal one, we reduce the atomic OD from 75 to 45 and change the coupling laser power from 0.85 to 0.35 mW. Because a high OD is not required now, we run the experiment more efficiently with a higher duty cycle of 30% [25]. As a control experiment, we first inject the anti-Stokes photons to the cavity, as illustrated in Fig. 4(a). Figure 4(b) shows the input and output waveforms before and after the cavity. The heralded anti-Stokes photon has nearly an exponential decay waveform except the oscillatory precursor structure in the leading edge. The estimated time constant is close to the cavity lifetime. In this case, the input and output waveforms overlap in the time domain and the photon has a significant probability of escaping from the cavity during the loading process.

Now we reverse the time and take the anti-Stokes photon as the trigger to herald its paired Stokes photon. We modify the optical setup to that shown in Fig. 4(d), where the cavity is placed to the Stokes photon side and its resonance is locked to the Stokes frequency. As shown in Fig. 4(e), the heralded Stokes photon has a nearly exponential growth waveform, which is the time reversal of that in Fig. 4(b). The cavity response as shown in the output waveform is similar to that in Fig. 2(e) and the overlap between the input and output waveforms is minimized. We obtain the experimental loading efficiency of $(60\pm5)\%$. This loading efficiency is lower than the value of the proof-of-principle demonstration mainly because of the unstorable optical precursor [26] and the deviation from the ideal exponential growth waveform. On the other side, compared the EOAM cases show in Fig. 2, the heralded single-photon generation rate is increased by a factor of about 30. As a measure of single-photon quantum nature, the measured $g_c^{(2)}$ is shown in Fig. 4(f).

In summary, we demonstrate efficient loading of a single photon into a single-sided Fabry-Perot cavity. We obtain loading efficiencies of $(87\pm2)\%$ for using heralded single photons shaped by an EOAM. Achieving a nearly unity loading efficiency is possible if one takes the rear mirror of the cavity with a higher reflectivity and a faster waveform generator. Moreover, we demonstrate the direct generation of heralded single Stokes photons with a nearly optimal waveform by adjusting the EIT parameters but without using the EOAM, and achieve a direct loading efficiency of $(60\pm5)\%$. We further verify the time reversal between the paired photons, which is originated from the frequency correlation of the two-photon entanglement. This direct loading efficiency may be possibly improved by applying other lossless biphoton waveform shaping techniques, such as modulating the temporal [29,30] or spatial [31] profiles of the driving classical laser fields.

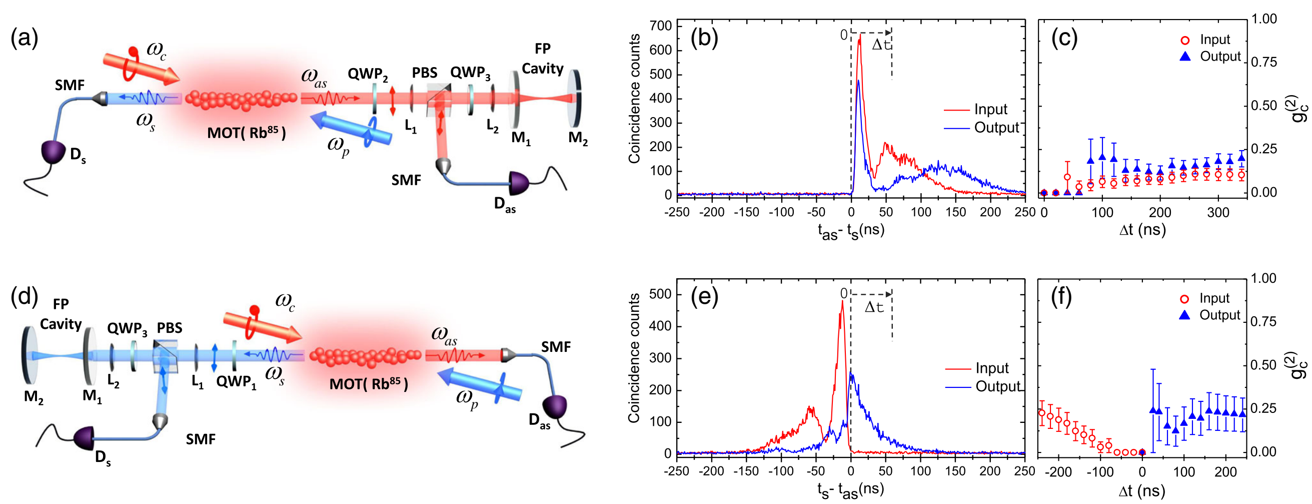

FIG. 4 (color online). Directly loading a single photon into the cavity without EOAM. (a) [(d)]: Experimental setup for loading heralded anti-Stokes [Stokes] photons into the cavity. (b) [(e)]: Input and output temporal waveforms of heralded anti-Stokes (Stokes) photons. (c) [(f)]: $g_c^{(2)}$ of the heralded anti-Stokes (Stokes) photons as a function of the coincidence time width. The coincidence counts in (b) and (e) are collected over 300 s.

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