Photonic switches with ideal switching contrasts for waveguide photons

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Photonic switches are one kind of key devices in quantum optical networks and have been demonstrated previously through either manipulating the cavity-atom interactions [Phys. Rev. Lett. **111**, 193601 (2013)] or driving the additional levels of the switch atoms [Phys. Rev. Lett. **106**, 113601 (2011)]. In this paper, we propose an alternative configuration generated by three empty cavities coupled in series to serve as an ideal photonic switch of the photons along the waveguide, i.e., photons are completely transmitted (reflected) if the three cavities are (are not) exactly resonant. It is shown that the quality of such a detuning-sensitive photonic switch is insensitive to the cavity-cavity, cavity-waveguide, and cavity-atom coupling strengths. The feasibility of the devices is also demonstrated with the current waveguide photonic technique.

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I. INTRODUCTION

It is well known that photons are ideal information carriers for long-distance secure optical quantum communication [1–3]. Therefore, high quality photonic switches are particularly important in various photonic circuits and optical quantum networks [4]. The robustness of the photonic switches require low loss, low signal-band noise, fast switching time, low distributions on the spatial, as well as polarization degrees of freedom of the transmitted photons [5].

Since there is no direct interaction between photons, one cannot control the transporting of one photon by manipulating that of another photon. Accordingly, considerable effort has been invested toward the achievement of photonic switches by manipulating the atoms in the context of cavity quantum electrodynamics (CQEDs) [6,7], wherein the tight confinement of photons in tiny volumes leads to drastic enhancement of the electric field associated with the cavity mode. The strong cavity-atom coupling yields various nonlinearities and atomic dressed states, implying modifying both the atomic emission spectra [8] and the transport features of the photons through the cavity [9]. This provides an effective approach for designing various desired photonic switches. However, a potential challenge in the CQED-based photonic switch is the switching time limited by the reciprocal atom-cavity coupling strength [10]. Also, the switching quality is suppressed by the unavoidable motion of the atom [11]. Basically, such kinds of switches are realized by controlling the atom-cavity interaction strength via tuning their spectral overlaps. The introduced temporal variations of the cavity frequency and thus the frequency chirps of the emitted photons [12] should decrease the reliability of the photonic switches [13]. In particular, if the rate of the input photons approaches that of the atomic excited-state decay, the resulting saturation behavior consequently will limit the performance of the switch [3].

Additionally, with the driving of the auxiliary atomic levels by classical control fields [14,15], recent works demonstrated that the ladder-type [16], Λ-type [17], and four-level [18,19] atomic configurations can be utilized to implement the switching behaviors towards the coupled waveguide photons. Unfortunately, the classical control fields used to drive the auxiliary atomic levels introduce practically various unwanted multiple-photon processes, which unavoidably disturb the single-photon features of the photonic switches [20]. Particularly, their switching velocities are strongly limited by the synchronicity of the applied control and the probe fields as well as their durations [21].

Differing from the typical schemes reviewed above, we propose here a robust way to implement the precise photonic switch with the ideal switching contrast by controlling the scatterings of the empty cavities. With such a cavity configuration, the ideal photonic switch could be implemented; the waveguide photon transmits completely if it is exactly resonant with the cavities, otherwise it is reflected completely. The detuning sensitivity of such a photonic switch is further verified by considering the influence of a two-level atom (TLA) embedded in the central cavity.

II. MODEL AND SOLUTIONS

We consider the configuration shown schematically in Fig. 1, wherein a black box as a quantum switch or filter consists of three empty cavities coupled in series whereas only the central one (i.e., cavity C) is coupled to the one-dimensional photonic waveguide. The Hamiltonian (with $\hbar = 1$) of the system reads as

$$
\begin{aligned}
H_{CC} = &\int dx\Big[C_f^{\dagger}(x)\Big(-iV_g\frac{\partial}{\partial x}\Big)C_f(x) \\
&+ C_b^{\dagger}(x)iV_g\frac{\partial}{\partial x}C_b(x)\Big] + \sum_{i=L,C,R}\omega_i M_i^{\dagger}M_i \\
&+ \sum_{i=b,f}\int dx\delta(x)V[C_i^{\dagger}(x)M_C + M_C^{\dagger}C_i(x)] \\
&+ \sum_{i=L,R}V_{Ci}[M_C^{\dagger}M_i + M_i^{\dagger}M_C]. \qquad (1)
\end{aligned}
$$

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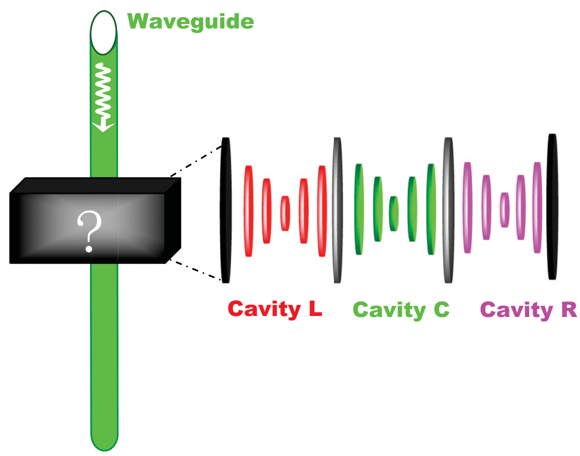

FIG. 1. Schematic of the photonic switch. The black box serving as a photonic switch is side coupled to a one-dimensional optical waveguide in which the photons depicted as wiggly waves propagate along it. The black box contains three empty cavities coupled in series with only the central cavity side coupling to the waveguide. The frequencies of cavities are detuned as $\omega_L = \omega_C - \Delta_L$ and $\omega_R = \omega_C + \Delta_R$.

Here, V_g is the group velocity of the waveguide photons with $C^\dagger_{f/b}(x)$ $[C_{f/b}(x)]$ being the bosonic creation and annihilation operators of a forward- or backward-moving photon at position x. ω_i $(i = L,C,R)$ is the resonance frequency of the ith cavity mode with the bosonic creation (annihilation) operator $M_i^\dagger$ (M_i). $\delta(x)$ signals that the interaction between the central cavity and the waveguide occurs only at $x = 0$. V is the coupling strength between the central cavity and the waveguide, and V_{CL} (V_{CR}) is the coupling strength between the central and the left (right) auxiliary cavities [22–25].

In this paper, we concentrate on the transport of single photons. Therefore, the most general eigenstate of the Hamiltonian H_{CC} can be expressed as

$$|\Psi\rangle_{CC} = \int dx[\phi_f(x)C_f^\dagger(x)|0\rangle + \phi_b(x)C_b^\dagger(x)|0\rangle] + \sum_{i=L,C,R} e_i M_i^\dagger|0\rangle, \tag{2}$$

with $\phi_f(x)$ $[\phi_b(x)]$ being the probability amplitudes of forward- (backward-) moving photons and e_i as the excited amplitude of the ith single-mode cavity. State $|0\rangle$ refers to the vacuum without any photon in the waveguide and cavities. Phenomenally, the spatial dependence of the photonic amplitudes can be rewritten as [26–28]

$$\begin{aligned}\phi_f(x) &= e^{ikx}[\theta(-x) + t\theta(x)],\\ \phi_b(x) &= e^{-ikx} r\theta(-x),\end{aligned} \tag{3}$$

with $\theta(x)$ being the step function and $k = \omega/V_g$. Obviously, $T = |t|^2$ $(R = |r|^2)$ is the reflected (transmitted) probability of the photon (with the frequency ω) input from $-\infty$ and scattered by the black box. Solving the eigenvalue equation $H_{CC}|\Psi\rangle_{CC} = \omega|\Psi\rangle_{CC}$, we get

$$t = \frac{S}{D}, \quad r = \frac{VK}{iV_g D}, \tag{4}$$

and

$$e_C = \frac{K}{D}, \quad e_L = \frac{V_{CL}K}{D(\omega - \omega_L)}, \quad e_R = \frac{V_{CR}K}{D(\omega - \omega_R)}, \tag{5}$$

with $S = (\omega-\omega_C)(\omega-\omega_L)(\omega-\omega_R) - V_{CL}^2(\omega-\omega_R) - V_{CR}^2(\omega - \omega_L)$, $D = (\omega - \omega_C + iV^2/V_g)(\omega - \omega_L)(\omega - \omega_R) - V_{CL}^2(\omega - \omega_R) - V_{CR}^2(\omega - \omega_L)$, and $K = V(\omega - \omega_L)(\omega - \omega_R)$.

III. DETUNING-SENSITIVE TRANSMISSION OF THE WAVEGUIDE PHOTONS

Originally, we consider the scattering of the waveguide photon by the central cavity, i.e., $V_{CL} = V_{CR} = 0$. The transmission amplitude in Eq. (4) reduces to $t = (\omega - \omega_C)/(\omega - \omega_C + i\Gamma)$ with $\Gamma = V^2/V_g$, and consequently, the transmission spectra are determined as $T(\Delta_C) = (\Delta_C^2)/(\Gamma^2 + \Delta_C^2)$ and $\Delta_C = \omega - \omega_C$. Due to the inevitably coherent interference between the incident photon along the waveguide and the emitted photon from the excited cavity, the incident photon with resonant frequency (i.e., $\omega = \omega_C$) is completely reflected. More generically, Fig. 2(a) shows that, if one needs to control the transport of the waveguide photons, the frequency of the central cavity should effectively be modulated. In what follows, we show this difficulty could be overcome by introducing the aside-coupling cavities.

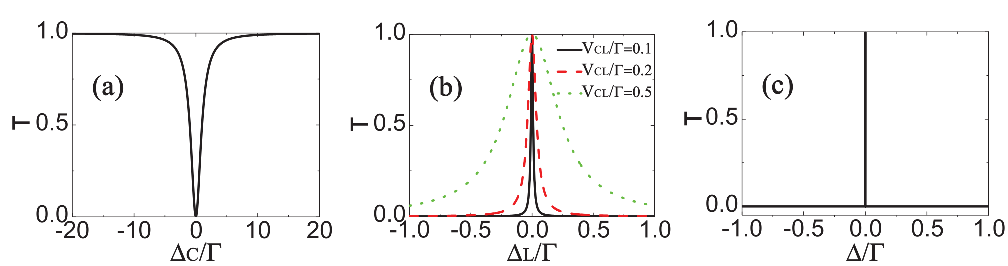

FIG. 2. The detuning-dependent transmission spectra of the waveguide photons. (a) Two aside cavities decouple from the central cavity, i.e., $V_{CL} = V_{CR} = 0$. Here, $\Delta_C = \omega - \omega_C$. It is clear that the resonant photon (i.e., $\Delta_C = 0$) is completely reflected, whereas the frequency shift required to switch the resonant photon from complete transmission to complete reflection is obviously larger than Γ. (b) An aside empty cavity is coupled to the central resonant cavity $(\omega = \omega_C)$, e.g., $V_{CL} \neq 0$, $V_{CR} = 0$, and $\Delta_L = \omega_L - \omega_C$. The frequency shift required to be a photonic switch can be narrower than Γ, but the transmission spectra varying from 0% to 100% depend on the ratio between the coupling strengths of cavity cavity and cavity waveguide. (c) Two aside resonant cavities couple to the central cavity with $\omega_C = \omega$ and $\Delta_L = \Delta_R = \Delta$. It is shown that the ideal photonic switch or filter with a zero-width window of the resonant photon (i.e., $\omega = \omega_C$) can be realized.

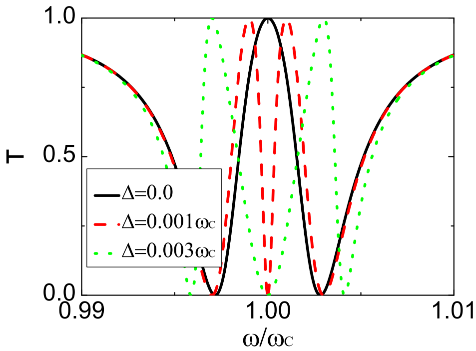

FIG. 3. The transmission spectra of the waveguide photons with $\Gamma = 0.0036\omega_C$ and $V_C = 0.002\omega_C$. It is seen that the detunings between the left and the right cavities induce the splits of the transmitted dips.

First, one aside cavity is introduced to couple the central cavity, e.g. ($V_{CL} \neq 0$ and $V_{CR} = 0$) for modulating the photonic transport. For this case the transmission amplitude in Eq. (4) becomes $t = [(\omega - \omega_C)(\omega - \omega_L) - V_{CL}^2]/[(\omega - \omega_C + i\Gamma)(\omega - \omega_L) - V_{CL}^2]$, and the relevant transmission spectra of the resonant waveguide photon (i.e., $\omega = \omega_C$), depending on the detuning $\Delta_L (= \omega_C - \omega_L)$ between the two cavities, reads as $T(\Delta_L) = V_{CL}^4/(\Gamma^2\Delta_L^2 + V_{CL}^4)$. As diagramed in Fig. 2(b), the resonant photon reflected completely by the central cavity in the previous configuration (i.e., without the coupling with the aside cavity) can now be transmitted through the central cavity, although a transmitted window exists on the detuning between the cavities. For defined cavity-cavity and cavity-waveguide coupling strengths, e.g., $V_{CL} = 0.1\Gamma$, the detuning width for shifting the transmitted probability of the resonant photon between zero and 1 is about 0.31Γ.

We next consider the central cavity coupling to two aside empty cavities with frequencies ω_L and ω_R, respectively. Without loss of the generality, we assume that $\omega_L = \omega_C - \Delta$, $\omega_R = \omega_C + \Delta$, and $V_{CL} = V_{CR} = V_C$. The transmission amplitude of the photon scattered by the present three-cavity configuration in Eq. (4) is reduced as $t = [(\omega - \omega_C)^3 - (\omega - \omega_C)\Delta^2 - 2V_{CL}^2(\omega - \omega_C)]/[(\omega - \omega_C)^3 - (\omega - \omega_C)\Delta^2 + i\Gamma(\omega - \omega_C)^2 - i\Gamma\Delta^2 - 2V_{CL}^2(\omega - \omega_C)]$. The detuning-dependent transmission of the resonant photon is plotted in Fig. 2(c), which shows clearly that: (i) If the three cavities are resonant ($\Delta = 0$), the resonant photon is transmitted completely; and (ii) once the three cavities have nonzero detunings, i.e., $\Delta \neq 0$, the resonant photons are completely reflected, i.e., $T = 0$. This indicates that the present three-cavity configuration aside coupled to the waveguide can be served as a photonic switch with the ideal switching contrast [29], i.e., $(T_{\text{resonance}} - T_{\text{detuning}})/(T_{\text{resonance}} + T_{\text{detuning}}) = 1$.

We now investigate the transport properties of the nonresonant incident photons scattered by the three-cavity device demonstrated above. Figure 3 shows how the transmitted probability depends on the frequency of the incident wave photon. It is seen that the resonant three-cavity device (i.e., $\Delta = 0$) splits the one transmission dip (i.e., the completely reflected point) of the single-cavity device [shown in Fig. 2(a)] into two dips. Physically, the cavity-cavity coupling results in the eigenfrequency splitting of the central cavity from single-mode ω_C to the supermodes $\omega_{1,2} = \omega_C \pm \sqrt{2V_C^2}$ [30], which means that the incident photon with the frequency $\omega_{1,2}$ will be reflected completely. Also, if the cavities exist detuning, i.e., $\Delta \neq 0$, then the transmitted dip of the incident photon splits into three dips, corresponding to the three nondegenerate eigenmodes, $\omega_{1,2} = \omega_C \pm \sqrt{2V_C^2 + \Delta^2}$ and $\omega_3 = \omega_C$. Given that the frequency distance between the complete transmission and the complete reflection is very small, the switch quality of the present three-cavity device for the resonant photon is sufficiently high, at least, theoretically. The detuning sensitivity of the device implies that, only when the device is set at the resonant case with $\Delta = 0$, is the resonant photon completely transmitted through the central cavity; otherwise it is reflected completely [i.e., $T(\omega_C) \equiv 0$] for any nonzero detuning setting.

Additionally, the aside-coupling cavities could be used to modulate the transport of the waveguide scattered by the central cavity with a TLA embedded. Indeed, if a TLA is embedded in the central cavity, the Hamiltonian (1) is modified as

$$H_{CA} = H_{CC} + \sum_{i=g,e} \Omega_i a_i^\dagger a_i + g[M_C a_e^\dagger a_g + M_C^\dagger a_g^\dagger a_e], \quad (6)$$

where $a_{g(e)}^\dagger$ and $a_{g(e)}$ are creation and annihilation operators of the ground (excited) state of the TLA, respectively. $\Omega_e - \Omega_g = \Omega$ is the resonant energy of the TLA, and g the coupling strength between the central cavity and the TLA. Obviously,

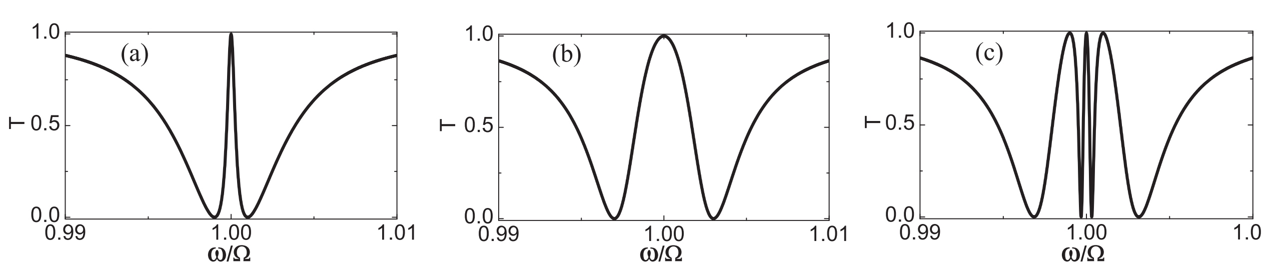

FIG. 4. Transmission spectra of the waveguide photons scattered by the proposed three-cavity device with a two-level atom embedded in the central cavity. Here, the cavity-atom coupling strength is set specifically as $g = 0.001\Omega$ and $\Gamma = 0.0036\Omega$. (a) The eigenfrequency of the central cavity reveals the usual Rabi splittings for $V_{CL} = V_{CR} = 0$. (b) The Rabi splitting of the central cavity is broadened by resonant interaction between the central cavity and the two aside cavities, i.e., $V_{CL} = V_{CR} = 0.002\Omega$ and $\Delta_L = \Delta_R = 0$. (c) The nonresonant couplings between the aside cavities and the central cavity (i.e., $V_{CL} = V_{CR} = 0.002\Omega$ and $\Delta_L = \Delta_R = 0.001\Omega$) yield the four dips (three peaks) of the transmission spectra of the waveguide photons.

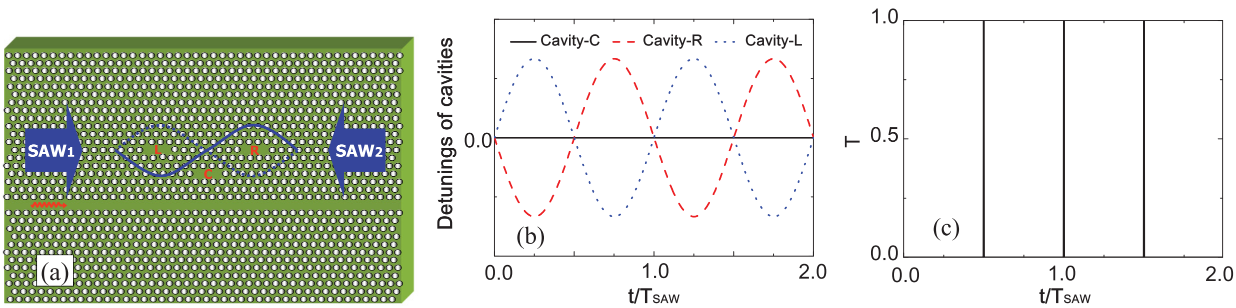

FIG. 5. Schematic of the experimental design for the detuning sensitive photonic switch. (a) Three photonic crystal cavities, L, R, and C, driven by a standing wave formed by two identical SAWs. Cavity C is placed in the node, and cavities L and R with a distance of half the wavelength are intentionally located in the antinodes of the standing wave. (b) The resonant frequencies of the cavities versus the time with T_{SAW} being the SAW period. (c) Transmission spectra of resonant waveguide photons modulated by the standing wave.

the eigenstate of H_{CA} can be simplified as

$$|\Psi\rangle_{CA} = \int dx[\phi_f(x)C_f^\dagger(x)|0,\_\rangle + \phi_b(x)C_b^\dagger(x)|0,\_\rangle] + \sum_{i=L,C,R} e_i M_i^\dagger|0,\_\rangle + e_A a_e^\dagger a_g|0,\_\rangle, \tag{7}$$

where $|0,\_\rangle$ is the vacuum with the TLA in the ground state and zero photon in the waveguide and the cavities. e_A is the excitation amplitude of atomic state $|e\rangle$. Following the same procedure for the system with the Hamiltonian (1), the transmission amplitude of the waveguide through the present device can be obtained as

$$t = \frac{S_2}{D_2}, \tag{8}$$

with $S_2 = (\omega - \omega_C)(\omega - \Omega)(\omega - \omega_L)(\omega - \omega_R) - g^2(\omega - \omega_L)(\omega - \omega_R) - V_{CL}^2(\omega - \Omega)(\omega - \omega_R) - V_{CR}^2(\omega - \Omega)(\omega - \omega_L)$ and $D_2 = (\omega - \omega_C + i\frac{V^2}{V_g})(\omega - \Omega)(\omega - \omega_L)(\omega - \omega_R) - g^2(\omega - \omega_L)(\omega - \omega_R) - V_{CL}^2(\omega - \Omega)(\omega - \omega_R) - V_{CR}^2(\omega - \Omega)(\omega - \omega_L)$. It is well known that the existence of the TLA in the cavity modifies the photon transport behaviors, e.g., yield the Rabi splittings in the photonic transmission spectra. Typically, Fig. 4 shows these modifications for the certain parameters, e.g., $g = 0.001\Omega$, $\Gamma = 0.0036\Omega$, $V_{CL} = V_{CR}$, and $\Delta_L = \Delta_R$. Indeed, without the aside two cavities L and R, the TLA splits the transmission dip (i.e., reflection peak), shown in Fig. 2(a), of the photon through the central cavity into two dips; the completely reflected point originally at $\omega = \omega_C$ has now been shifted to $\omega_{1,2} = \Omega \pm g$ [31]. This is the well-known Rabi splittings. Figure 4(b) shows that, when the two aside cavities resonantly couple to the central cavity, such a splitting is further broadened $\omega_{1,2}=\Omega\pm\sqrt{2V_{CR}^2+g^2}$. Furthermore, Fig. 4(c) shows that, if the two aside cavities couple to the central cavity have certain detunings, the transmission dip shown in Fig. 4(b) is split into four dips; each dip corresponds to one of the four modified nondegenerate eigenfrequencies $\omega_{1,2}=\Omega-\sqrt{X\pm\sqrt{X^2-g^2\Delta_R^2}}$, $\omega_{3,4}=\Omega+\sqrt{X\pm\sqrt{X^2-g^2\Delta_R^2}}$ with $X = (\Delta_R^2 + g^2 + 2V_{CR}^2)/2$. This indicates again that the transmission properties of photons along the waveguide can effectively be controlled by coupling a pair of aside empty cavities to the central cavity no matter whether it contains a TLA or not.

IV. CONCLUSIONS AND DISCUSSIONS

To summarize, a scheme to realize the ideal photonic switch of the waveguide photons is proposed through introducing a pair of aside cavities to couple the central cavity. Originally, the transport behavior of the waveguide photon is modulated by the central cavity. However, such a switch behavior requires a sufficiently wide frequency window implemented by adjusting the frequency of either the central cavity or the incident photons. In this paper a relatively simple approach was proposed to overcome such a difficulty by introducing a pair of aside cavities to modulate the frequency of the central cavity.

Our proposal can be realized with the current surface acoustic waves (SAWs) [32,33] and photonic crystal cavities (PCCs) [13,21,34,35] as depicted in Fig. 5. The standing waves with controllable frequencies in the device can be excited by the SWA drivings. The distances among cavities L and R, cavity L/R, and the waveguide, could be set large enough such that only cavity C is coupled to the waveguide. Due to the SAW straining (stressing) the PCCs, shown schematically in Fig. 5(b), the effective length of the cavity could be adjusted to increase or reduce properly such that cavities L and R in turn yield to red- and blue-side band resonances and the frequency of cavity C is still kept unchanged. As a consequence, when the SAW with the frequency, e.g., $f_{\mathrm{SAW}} = 1.703$ GHz, is generated by applying a +17-dBm short radio-frequency voltage pulse to interdigital transducer electrodes, the cavity wavelength shift could be modulated within 1.2 nm [33]. Consequently, as shown in Fig. 5(c), the resonant waveguide photon is completely transmitted only when $t = \frac{1}{2}nT_{\mathrm{SAW}}$ with $n = 1$–3, ... Therefore, the present three PCCs driven by two SAWs can really be served as a high quality photonic switch.

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