# Electrically controlled optical switch in the hybrid opto-electromechanical system*

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To promote the future quantum information technologies, we demonstrate an electrically driven optical switch based on quantum interference in a hybrid opto-electromechanical system, which consists of an opto-mechanical cavity and an external electric circuit. The key element of our scheme is a moveable mirror of cavity as a charged mechanical oscillator capacitively coupled to a fixed charged plate in a variable capacitor. By adjusting the voltage of the capacitor, the displacement of the moveable mirror is modulated, then the cavity field can be electrically turned on or off due to the detuning of the cavity. Based on the cavity induced transparency, the transparency window can be electrically switched on or off by turning on or off the cavity field. Therefore, the susceptibility of the medium in the cavity can be electrically controlled, i.e., the scheme of the electrically controlled absorption switching can be demonstrated. This electrically driven optical switch will excite a development trend and implementation prospect towards the integration and miniaturization of quantum module device in a chip.

**Keywords:** electromechanical systems, cavity induced transparency, optical switch

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## 1. Introduction

It has long been appreciated that cavity quantum electrodynamics (QED) has been studied from many different points,[1] especially, quantum coherence effect of a light–matter interaction system in the cavity plays an important role in enhancing and controlling the optical property of the medium. An outstanding instance is cavity induced transparency (CIT),[2] which is an electromagnetically induced transparency (EIT)-like effect. In EIT,[3] when the two metastable states couple to a common excited state by the control and probe fields, the susceptibility of the probe field in the medium is largely modified through the destructive quantum interference of the amplitudes of the two optical transitions.[4] This ability to modify the susceptibility has revealed many new phenomena in quantum optics, such as the optical switch, the storage of light, and quantum memory.[5] CIT effect will occur by replacing the control field with the cavity field when the interactive EIT-medium is trapped inside the optical cavity.

A popular optomechanical cavity consisted of a fixed and a moveable cavity mirrors has been proposed and studied due to its potential applications in high precision measurements and quantum information processing in recent years.[6] In this device, the moveable mirror can be driven by the radiation pressure force from the cavity field as a mechanical resonator (MR).[7–10] Recently, optomechanically induced transparency (OMIT) effect, normal mode splittings, quantum state conversion and pulse transmission have also been observed in such a system.[11–14] The storing optical information has been experimentally demonstrated as a mechanical excitation in a silica optomechanical resonator.[15,16] The crucial component of such an optomechanical system is micomechanical or nanomechanical resonator, which can be efficiently coupled to the different devices as an effective quantum interface. A prototype example is the electromechanical system, in which the MR can be coupled either capacitively or inductively with an electric circuit.[17–19]

Optical switch is a core part of optical networks and information communication technology. An optical switch where a laser pulse controls absorption of another laser field at a different frequency was theoretically proposed by Harris and Yamamoto in a four-level EIT atomic systems based on quantum interference.[20] Then this photon switching was experimentally demonstrated in a four-level $^{87}$Rb atomic system.[21] Recently, researchers have reported that a nearly perfect switch-

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ing of the transmission of the probe field was demonstrated using cavity EIT by applying a weak switching field.[22] Many recent other works on optical switches have been presented, such as optical switches in two-level atom,[23] three-level atom,[24] four-level atom system,[25] all optical switch of vacuum Rabi oscillations,[26] mechanical switch in dual-cavity optomechanical systems,[27] fiber-optical switch controlled by a single atom,[28] etc. These schemes mainly focus on the control of one light field by another.

In this paper, we present an electrically controlled optical switch in a hybrid opto-electromechanical (HOEM) device. This device is made up of the MR of an optomechanical cavity coupled capacitively to a fixed conductive plate in a variable capacitor, hence it involves the advantages of the cavity and the conveniently electrical control. This similar model is attracting the great attention. The interesting phenomena have been presented, such as the entanglement,[29] state transfer,[30] electromagnetically induced absorption,[31] and so on. Recently, we have reported an electrically controlled quantum memories and dark-state polaritons.[32] In this work, a variable capacitor is induced in our model. By changing the voltage on the capacitor, the cavity filed can be modulated to engineer the susceptibility of the medium based on CIT. Here we demonstrate that by sending the different electric voltage pulses on the capacitor, the probe absorption can be switched on or off.

Comparing with the traditionally optical control scheme, our model has the following advantages: (i) The cavity field in the high-Q cavity acts as the control field, the coupling strength between the cavity field and the medium is effectively enhanced. (ii) Based on the CIT, the cavity is turned off or on by changing the voltage on the capacitor. Therefore, the optical switching can be electrically manipulated in the hybrid opto- and electro- mechanical system. (iii) The optical switching can be electrical optimized by the shapes of the voltage waveforms. This capacitive modulation is simple and compact for the integration and application. It is well known that an electrical control is preferable to the optimal control towards the integration and miniaturization. Therefore the adjustment of the optical switch should be improved from the optically to electrically driven ways in order to the practical application.

This paper is organized as follows. In Section 2, we present the model and Hamiltonian. Then in Section 3, we focus on the equations of system. In Section 4, the probe absorption and the dispersion in the HOEM system is analyzed. The electrically controlled optical switch is demonstrated. We briefly summarize the results in Section 5.

## 2. Model Hamiltonian

The HOEM system considered in this paper consists of a standard optomechanical cavity and an electric circuit shown in Fig. 1(a). The optomechanical cavity is made of a cavity with one fixed and one moveable mirrors. As a charged mechanical oscillator (CMO), the moveable mirror can be charged with the positive charge $Q$ and coupled capacitively to a fixed conductive plate that is supplied with negative charge $-Q$ by a voltage waveform with the time regime $T$ from a waveform generator. Thus the CMO and the fixed conductive plate form a mechanically variable capacitor. The photon is resonantly injected into the cavity by the input field $\varepsilon_c$ with frequency $\omega_c$. The CMO with the frequency $\omega_m$ and the mass $m$ is driven by the radiation pressure from the cavity field with frequency $\omega_0$ and the Coulomb interaction from the capacitor. An ensemble of $N$ identical $\Lambda$-type three-level atoms is trapped inside the high-Q cavity with length $L$. Each atom is assumed to have $\Lambda$-type dipole transitions shown in Fig. 1(b). A weak probe field $E_{\rm p}$ with frequency $\omega_{\rm p}$ is detuned by $\Delta_{\rm p}$ from $|b\rangle$ to $|a\rangle$ transition. The cavity field with the detuning $\delta$ from $|c\rangle$ to $|a\rangle$ transition is used to coherently manipulate the propagation of the probe field. The total Hamiltonian of the model reads $H = H_0 + H_{\rm i}$, where $H_0$, the free Hamiltonian of the model, is given explicitly by

$$H_0 = \hbar\omega_0 a^\dagger a + \left(\frac{p^2}{2m} + \frac{1}{2}m\omega_m^2 q^2\right) + \hbar\omega_{ba}\sum_{i=1}^{N}\sigma_{aa}^i + \hbar\omega_{bc}\sum_{i=1}^{N}\sigma_{cc}^i. \quad (1)$$

The first term describes the energy of the cavity mode characterized by the annihilation (creation) operator $a$ ($a^\dagger$) with the commutation relation $[a, a^\dagger] = 1$. The second term corresponds the energy of the CMO with the position $q$ and momentum $p$. The third term describes the energy of the $N$ three-level $\Lambda$ atoms with $\sigma_{\alpha\beta}^i = |\alpha\rangle_{ii}\langle\beta|$ $(\alpha, \beta = a, b, c)$, where $\omega_{ba}$ $(\omega_{bc})$ is the energy-level spacing between $|a\rangle_i$ $(|c\rangle_i)$ and $|b\rangle_i$ of the $i$-th atom with the ground state $|b\rangle_i$ as an energy reference point. $H_{\rm i}$, the interaction Hamiltonian of the various subsystems, is given by

$$H_{\rm i} = -\hbar G_0 a^\dagger a q + {\rm i}\hbar\varepsilon_c(a^\dagger {\rm e}^{-{\rm i}\omega_c t} - a{\rm e}^{{\rm i}\omega_c t}) - \sum_{i=1}^{N}(\hbar g_{\rm p} E_{\rm p}\sigma_{ab}^i + \hbar g a\sigma_{ac}^i + {\rm H.c.}) - U^2\eta(q+r). \quad (2)$$

The first term comes from the radiation-pressure coupling of the cavity field to the CMO with the optomechanical coupling rate $G_0 = \omega_c/L$. The second term describes the input-output relations of the cavity field with the strength $\varepsilon_c = \sqrt{2P_{\rm c}\kappa/\hbar\omega_c}$ of the input driving field related to the laser power $P_{\rm c}$ and the cavity decay rate $\kappa$. The third term describes the two dipole transitions with the coupling strength $g_{\rm p}$ and $g$ corresponding to the probe field $E_{\rm p} = \varepsilon_{\rm p}{\rm e}^{-{\rm i}\omega_{\rm p}t}$ with the strength $\varepsilon_{\rm p}$ and the cavity field. The last term presents the Coulomb interaction between the CMO and the fixed charged plate approximated

as $V_c \approx -U^2\eta(q+r)$ for $q \ll r$,[32] where $\eta = \varepsilon_0 S/2r^2$, $\varepsilon_0$ is the vacuum permittivity, $U$ is the voltage, $S$ is the area, and $r$ is the distance between two capacitive plates. Here the Coulomb force on the CMO points to the same direction as the radiation pressure force on the CMO.

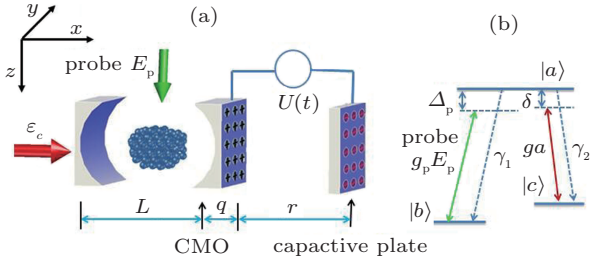



**Fig. 1.** (color online) (a) The optomechanical system is composed of an optomechanical cavity and a variable capacitor. The voltage $U(t)$ on the capacitor is supplied by a voltage waveform generator. An ensemble of $N$ identical $\Lambda$-type three-level atoms is trapped inside the cavity. (b) The level structure of the $i$-th atom coupling to the probe ($|b\rangle$ and $|a\rangle$) and cavity ($|c\rangle$ and $|a\rangle$) fields. $\gamma_1$ and $\gamma_2$ are the decay rates from $|a\rangle$ to $|b\rangle$ and $|c\rangle$, respectively. The detunings are $\Delta_p = \omega_{ab} - \omega_p$ and $\delta = \omega_{ac} - \omega_c$.

## 3. Heisenberg–Langevin equations

In the slowly varying amplitude and weak-field approximations, assuming the most of the atoms are in the collective ground state at all times,[33,34] i.e., $\langle\sigma^i_{bb}\rangle \approx 1$, $\langle\sigma^i_{aa}\rangle \approx \langle\sigma^i_{cc}\rangle \approx 0$. Thus the averages of collective operators $(1/N)\sum_{i=1}^N \sigma^i_{aa}$ and $(1/N)\sum_{i=1}^N \sigma^i_{cc}$ are much smaller than one due to the low excitation in the excited states $|a\rangle$ and $|c\rangle$, however $(1/N)\sum_{i=1}^N \sigma^i_{bb}$, $(1/N)\sum_{i=1}^N \sigma^i_{ba}$, and $(1/N)\sum_{i=1}^N \sigma^i_{bc}$ are large quantities due to the large number of atom in the ground state $|b\rangle$. Moreover, the small contributions of the average of the operator $(1/N)\sum_{i=1}^N \sigma^i_{ca}$ (characterizes the transitions between two upper levels) can be neglected.[33] The dynamic equations of the system governed by the Hamiltonian $H$ are depicted as

$$\begin{aligned}
\partial_t q &= \frac{p}{m},\\
\partial_t p &= -m\omega_m^2 q - \gamma_m p + \hbar G_0 a^\dagger a + U^2\eta,\\
\partial_t a &= [-\kappa - \mathrm{i}(\omega_0(q) - G_0 q)]a + \varepsilon_c \mathrm{e}^{-\mathrm{i}\omega_c t},\\
\partial_t A &= (-\gamma_1 - \mathrm{i}\omega_{ba})A + \mathrm{i}g_p\varepsilon_p \mathrm{e}^{-\mathrm{i}\omega_p t} + \mathrm{i}gaC,\\
\partial_t C &= (-\gamma_2 - \mathrm{i}\omega_{bc})C + \mathrm{i}ga^\dagger A,
\end{aligned} \tag{3}$$

where $\gamma_m$ is the damping of CMO. The collective operators of the atomic ensemble are defined as: $A = (1/N)\sum_{i=1}^N \sigma^i_{ba}$ and $C = (1/N)\sum_{i=1}^N \sigma^i_{bc}$, which satisfy the commutation relations given by $[A,C] = 0$, $[A,C^\dagger] \approx 0$, $[A,A^\dagger] \approx 1$, $[C,C^\dagger] \approx 1$ in Refs. [33]–[35].

In the following calculations, we are interested in the steady-state equations. To obtain the steady-state solutions, let us first remove the fast varying factors by the rotating transformations $a = \tilde{a}\mathrm{e}^{-\mathrm{i}\omega_c t}$, $A = \tilde{A}\mathrm{e}^{-\mathrm{i}\omega_p t}$, $C = \tilde{C}\mathrm{e}^{-\mathrm{i}(\omega_p-\omega_c)t}$.[33] In the rotating frame, the dynamic equations in Eq. (3) become

$$\begin{aligned}
\partial_t q &= \frac{p}{m},\\
\partial_t p &= -m\omega_m^2 q - \gamma_m p + \hbar G_0 \tilde{a}^\dagger \tilde{a} + U^2\eta,\\
\partial_t \tilde{a} &= (-\kappa - \mathrm{i}\Delta_0)\tilde{a} + \varepsilon_c,\\
\partial_t \tilde{A} &= (-\gamma_1 - \mathrm{i}\Delta_p)\tilde{A} + \mathrm{i}g_p\varepsilon_p + \mathrm{i}g\tilde{a}\tilde{C},\\
\partial_t \tilde{C} &= [-\gamma_2 - \mathrm{i}(\Delta_p - \delta)]\tilde{C} + \mathrm{i}g\tilde{a}^\dagger\tilde{A},
\end{aligned} \tag{4}$$

where $\Delta_0 = \Delta - G_0 q$ and $\Delta = \omega_0(q) - \omega_c$. In the steady-state regime, all the time derivatives of the operators in Eq. (4) are equal to zero,[33] then the mean solutions of the steady-state equations can be derived as

$$\begin{aligned}
\langle p\rangle_s &= 0,\\
\langle q\rangle_s &= \frac{\hbar G_0 n_p + U^2\eta}{m\omega_m^2},\\
\langle n_p\rangle_s &= \langle\tilde{a}^\dagger\tilde{a}\rangle = \frac{|\varepsilon_c|^2}{\kappa^2 + \Delta_0^2},\\
\langle\tilde{A}\rangle_s &= \frac{\mathrm{i}g_p\varepsilon_p[\gamma_2 + \mathrm{i}(\Delta_p - \delta)]}{(\gamma_1 + \mathrm{i}\Delta_p)[\gamma_2 + \mathrm{i}(\Delta_p - \delta)] + g^2(\langle n_p\rangle_s + 1)}.
\end{aligned} \tag{5}$$

From Eq. (5), we can find that the motion of the CMO can be completely modulated by the voltage when the radiation pressure force is much less than the Coulomb force.[32] Furthermore, the number of photons inside the cavity $n_p$ depends on the intensity of the injected optical field (input-output relation), the decay of cavity ($\kappa$) and the detuning subjected to the displacement $q$ of the CMO. Initially, the cavity is on resonance with the injected optical field, i.e., when $q = 0$, $\Delta_0 = 0$. When the voltage is added on the capacitor, the CMO will move, then the total cavity length is changed. Namely, the resonance frequency of the cavity is electrically adjusted ($\omega_0(q) \approx \omega_0 - G_0 q$). This induces the increasing loss of the photons to achieve the electrically controlled cavity field. Therefore, the electrically controlled CMO and cavity field can be given by

$$\begin{aligned}
\langle q\rangle_s &= \frac{U^2\eta}{m\omega_m^2},\\
\langle n_p\rangle_s &= \frac{|\varepsilon_c|^2}{\kappa^2 + \left(\dfrac{2G_0\eta}{m\omega_m^2}U^2\right)^2}.
\end{aligned} \tag{6}$$

Here we can define the effective cavity decay rate as

$$\kappa_{\mathrm{eff}} = \sqrt{\kappa^2 + \left(\frac{2G_0\eta}{m\omega_m^2}U^2\right)^2}$$

and quality factor of the cavity as $Q_{\mathrm{eff}} = \omega_c/\kappa_{\mathrm{eff}}$, which are dynamically modulated by changing the voltage on the capacitor.[32]

## 4. Electrically controlled absorption switching in the HOEM system

To explore the nonlinear absorption and dispersion of the probe light in our model, let us now study the susceptibility of

the atomic medium. The susceptibility of the atomic ensemble to the weak probe field $E_{\rm p}$ can be described by

$$\chi = \frac{\langle \tilde{p} \rangle}{\varepsilon_0 \langle \varepsilon_p \rangle}, \tag{7}$$

where the polarization $\tilde{p}$ of the atomic ensemble is

$$\langle \tilde{p} \rangle = \frac{\mu}{V} \sum_{i=1}^{N} \tilde{\sigma}_{ba}^{(i)}. \tag{8}$$

In the steady-state case, we can obtain the susceptibility

$$\chi = I\langle A \rangle / \langle \varepsilon_p \rangle, \tag{9}$$

where $I = \mu N/\varepsilon_0 V$ can be as a relative unit of the susceptibility and is proportional to the atomic density $N/V$. It is well known that the real part $\mathrm{Re}(\chi)$ and the imaginary part $\mathrm{Im}(\chi)$ of the susceptibility $\chi$ describe the dispersion and absorption of light, respectively.

It is well known that a technique can be used to make opaque atomic medium transparent by means of quantum interference, i.e., EIT, in which a strong control field that is at resonance with the transition between the metastable and excited state can be used to modify the propagation of a weak light field that couples the ground state to the same excited state in the atomic medium. In such a case, the pathways of two light can interfere and cancel each other. With such destructive quantum interference, the effect that the atoms can not be promoted to the excited states leads to a vanishing light absorption, i.e., the transparent window of the weak probe light without absorption appears by means of the control field. In our model, the cavity field is used to replace the control field in EIT and control the optical absorption of weak probe field in EIT-atomic medium, i.e., CIT. Because of the displacement of CMO governed by the voltage, the strength of the cavity field can be adjusted electrically by the off-resonant loss. Therefore, the voltage can effectively affect the susceptibility of the probe field in the atomic medium based on CIT. To illustrate this effect, figure 2 is plotted to present the dispersion and absorption of the probe light as a function of the detuning $\Delta_{\rm p}$ in the cases of the different voltages. As shown in Fig. 2, a non-absorption dip changes from broad to narrow and finally disappears as the voltage increases. It is worth noting that the order of magnitude of voltage can be modulated by changing $\eta$, i.e., change the values of $r$ and $S$. Therefore the transparent window can be turned off by increasing the voltage. When the voltage on the capacitor disappears by injecting the inverse voltage pulse to neutralize the charges on the plates, the cavity field recovers, then the transparency window appears again, i.e., the electrically driven optical switch is obtained in the HOEM cavity. In addition, here there is one advantage that the optimizations of the optical switching can be achieved by optimizing the shapes of the voltage waveforms in the experimental operations.

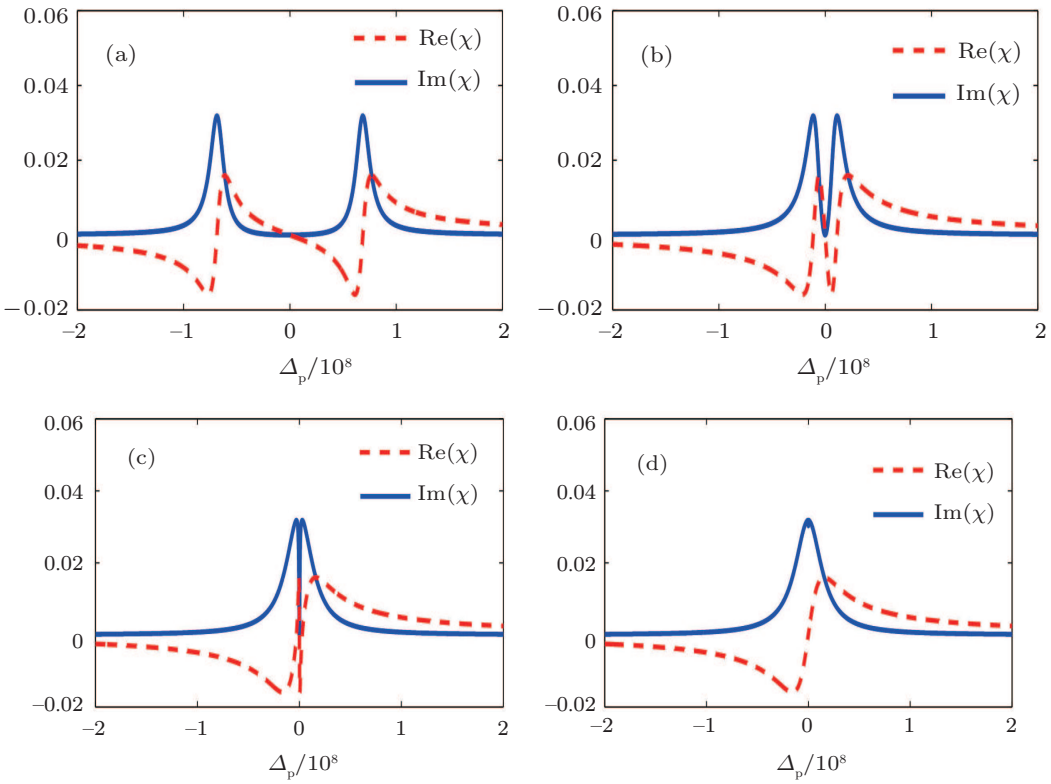



**Fig. 2.** (color online) The susceptibility as a function of the probe detuning in the cases of the different voltages. The blue solid (red dashed) line refers to the imaginary (real) part of the susceptibility with (a) $U = 0$, (b) $U = 5$, (c) $U = 10$, (d) $U = 100$, and the parameters are taken from the experiments in Refs. [36] and [37] as as $\delta = 0$, $\gamma_1 = 2\pi \times 2.5$ MHz, $\gamma_2 = 1$ kHz, $g_{\rm p} = 0.5$ MHz, $g/g_{\rm p} = \sqrt{3}$, $m = 145$ ng, $\omega_m = 2\pi \times 947$ kHz, $L = 25$ mm, $\kappa = 2\pi \times 215$ kHz, $S = 0.6$ mm$^2$, and and $r = 0.21$ μm.

To reveal the absorptive switching of the probe laser, we give the detail scheme as follows. Firstly an optical field $\varepsilon_c$ is resonantly injected into the cavity without the voltage and interacts with the atomic ensemble, then the population of atomic ensemble is then optically pumped into the ground state $|b\rangle$. The number of photons in the cavity will reach in balance. Afterwards, the weak probe pulse $E_p$ enters the cavity along the $z$ axis and interacts with the atomic medium, as shown in Fig. 1(b). In this case of two transition paths interference, the transparency window of the weak probe pulse is presented due to the strong cavity field without the voltage on the capacitor. Thus the absorption of the probe filed is absent with $\mathrm{Im}(\chi) = 0$ at first. Namely, the probe transmission through the atomic medium is initially turned on, as shown in Fig. 2(a). To turn off the transparency window, the error function of the voltage waveform $(U_0(1 - \mathrm{erf}(-t/20\Gamma)))$ is added to the capacitor by the voltage waveform generator, as shown in Fig. 3(a). As the voltage increases, the displacement of the CMO becomes large (see in Fig. 3(b)), then the cavity field decreases (see in Fig. 3(c)). Hence the transparency window gradually becomes small and then disappears, as shown in Figs. 2(b)–2(d). Namely, the absorption increases gradually as shown in Fig. 3(d). Therefore the probe transmission through the atomic medium is turned off. When the voltage generator sends to a reversed voltage $(U_0(1 - \mathrm{erf}(t/20\Gamma)))$, the charges on the capacitor are neutralized. The cavity field recovers and becomes enough strong. The standard CIT is again achieved by the quantum interference between the cavity field and probe field, as shown in the second half time of Fig. 3. The non-absorption probe field appears again. It is worth noting that the voltage pulse is very slow so that the system is stable state all time. In this way, the absorption switching is achieved by the electrically controlled quantum interference in the HOEM cavity. During the switching process from the absorption to non-absorption to absorption, the optical switch of the probe field can be periodically performed by the electrical manipulation.

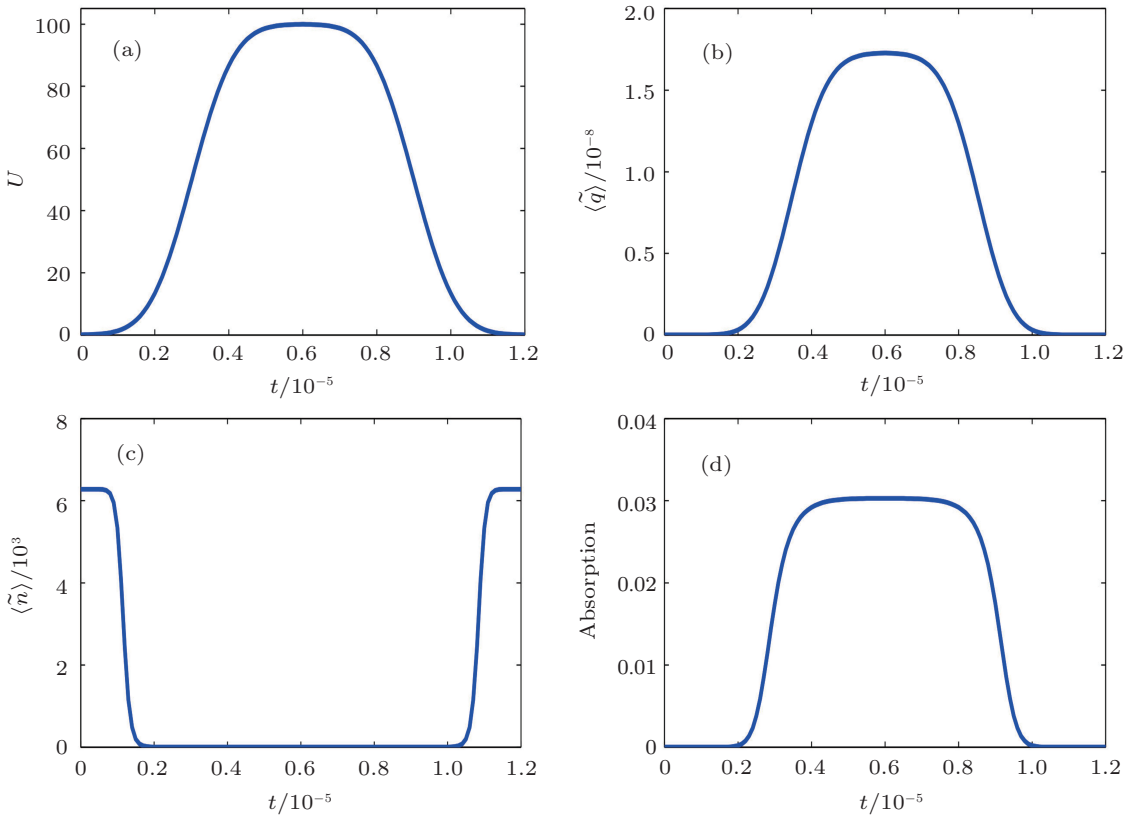



**Fig. 3.** (color online) The absorptive switching of a probe. When the error functions of voltage waveforms $(U_0(1 - \mathrm{erf}(\mp t/20\Gamma)))$ are successively injected in the capacitance, as shown in (a), the changes of the displacement of the CMO, the photon number in the cavity and the absorption of probe filed are plotted in panels (b), (c), and (d), respectively. The parameters are the same as those in Fig. 2.

## 5. Conclusions

We have studied the nonlinear optical properties with the dispersion and absorption of the probe photons in the HOEM system with an optomechanical cavity capacitively coupled an external circuit. A scheme of the absorptive photon switching in the EIT-atomic ensemble trapped inside the HOEM cavity was proposed based on CIT. By the variable capacitance, the cavity field as a control field can be effectively controlled to achieve the adjustment of the transparency window based on CIT mechanism. Therefore, the absorption or non-absorption of the weak probe can be switched on or off by modulating

the voltage. The scheme has an advantages: the sensitivity of optical switch can be adjusted by the capacitance with the distance and the area and the width of the voltage waveform. Furthermore, this electrically controlled optical switch is a development trend towards the integration and miniaturization in quantum information processing modules. The scheme proposed here is expected to be applied in the information process and quantum network in the future.

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