Microwave controlled optical double optomechanically induced transparency in hybrid piezo-optomechanical cavity system

Shi-Chao Wu,$^{1,2}$ Li-Guo Qin,$^3$ Jun Jing,$^4$ Tian-Min Yan,$^1$ Jian Lu,$^1$ and Zhong-Yang Wang$^1$,*

$^1$Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, 201210, China
$^2$University of Chinese Academy of Sciences, Beijing, 100049, China
$^3$Department of Physics and Electronics, Qingdao University of Technology, Qingdao, 266033, Shandong, China
$^4$Department of Physics, Zhejiang University, Hangzhou, 310027, Zhejiang, China

We propose a scheme that is able to generate the microwave controlled optical double optomechanical induced transparency (OMIT) in a hybrid piezo-optomechanical cavity system, which a piezoelectric optomechanical crystal AlN-nanobeam resonator is placed in a superconducting microwave cavity, and the AlN-nanobeam resonator can be simultaneously driven by both the optical field via the radiation pressure and the microwave field via the piezoelectric interaction. We show that in the presence of a strong pumped optical field applied to the optomechanical crystal cavity through the optical waveguide and an intensely stimulated microwave field applied to the superconducting microwave cavity, a double-OMIT window can be observed in the weak output probe field. The mechanism is that a N-type four-level system can be formed by the system, when two driving fields and a probe field are applied to the corresponding levels, under the effect of quantum interference between different energy level pathways, the third-order nonlinear absorption is enhanced by the constructive quantum interference while the linear absorption is inhibited by the destructive quantum interference, as a result, the double-OMIT window is generated. Our scheme can be applied to realize high-speed optical switches, high-resolution spectroscopy, coherent population trapping or quantum information processing in the solid state quantum systems.

PACS numbers: 42.50.Gy, 42.50.Wk, 41.20.Jb

I. INTRODUCTION

Mutual interaction between the optical field and the microwave field is an interesting research area and has been studied theoretically and experimentally in many fields, such as the coherent signal transfer [1–3], bidirectional conversion [4–6] or coherent coupling [7–10]. Those phenomena have been realized in many systems, in which a representative one of them is the optomechanical system. The traditional optomechanical system is consisted by the mechanical resonator and the optical field cavity or the microwave field cavity [11]. With the advantage of convenience for integration, the traditional optomechanical system has already been extended to various hybrid solid state quantum systems currently, including the combination with the optical lattice crystals [9], the piezoelectric materials [10], superconducting microwave field cavity [12], superconducting quantum circuits [13] and the like.

Since electromagnetically induced transparency (EIT) phenomenon was observed in three-level atomic systems [14, 15], many new EIT-related effects have also been studied theoretically and experimentally in various multiple-level systems [16–22], including the two-photon absorption phenomenon which was first proposed theoretically by Harris et al [17] and observed by Yan et al [18] in the N-type four-level system composed of cold Rb atoms. Two-photon absorption can generate the double-EIT phenomenon, which can be used to realize high-speed optical switches [23], high-resolution spectroscopy [24], cross-phase modulation [25], or quantum information processing [26] in various quantum systems.

Not merely in the natural atomic systems, an EIT-like phenomenon, which is called the optomechanical induced transparency (OMIT), has also been studied in various optomechanical systems [9, 27–33], such as the optomechanical crystal nanobeam cavity system [29]. Optomechanical crystal cavity nanobeam system is formed with periodic free-standing beam structure which used to create co-localized high-Q optical modes and mechanical resonances, and a large strength radiation-pressure-induced interaction between optical modes and mechanical resonances can be realized in this device [9]. The interaction between the optical modes and mechanical resonances can generate the OMIT, which is also a quantum interference phenomenon between different pathways.

Recently in some research experiments, the optomechanical crystal nanobeam has been made by the piezoelectric materials [7, 9, 34], such as AlN [7]. With the purpose that AlN is not only piezoelectric but also has a strong photoelastic effect, the AlN-mechanical resonator can be effectively driven by both the microwave field via the piezoelectric interaction and the optical field via the radiation pressure. Strong coupling between the microwave field and the mechanical resonator via piezoelectric interaction also has been realized recently, for instance in the superconducting microwave cavity systems [7, 35–37], the piezoelectric coupling strength can be designed exceeding $40 \times 10^6$ Hz [7, 36, 37].

Here we proposed a hybrid optical and microwave
piezo-optomechanical cavity system, which an optomechanical crystal AlN-nanobeam resonator is placed in a planar superconducting microwave cavity contactlessly, then the AlN-nanobeam mechanical resonator can be effectively driven by both the microwave field via the piezoelectric interaction and the optical field via the radiation pressure. We show that in the presence of a strong pumped optical field applied to the optomechanical crystal cavity through the optical waveguide and an intensely stimulated microwave field applied to the planar superconducting microwave cavity, a double-OMIT window can be observed in the output weak probe field, which is similar to the double-EIT observed in the nature atomic systems.

The reason for the occurrence of the double-OMIT is that a N-type four-level system can be formed by our scheme, with the driving of optical fields and the microwave field applied to the corresponding levels, the energy level of the mechanical resonator is split into two new levels by the piezomechanical coupling effect, then the third-order nonlinear absorption can be enhanced by constructive quantum pathway interference while the linear absorption be inhibited by destructive quantum pathway interference, as the result, the double-OMIT window is generated, and the relevant mechanisms have been extensively studied experimentally and theoretically [38, 39]. More importantly, as the double transparency window can be controlled by both the pumped optical field and the stimulated microwave field, our scheme can be applied to control the optical information processing via the microwave field.

The paper is organized as follows. In Sec.II we describe the proposed system firstly, with deriving the quantum Langevin equations of the system, the general analytical expression of the output field at the probe frequency is obtained subsequently. In Sec.III we present the feasibility of the double-OMIT with the parameters chosen based on recent experiments, and the corresponding physical mechanism is discussed in detail. In Sec. IV we study the variation of output field with the changing of driving field under different conditions. Finally a brief conclusion is summarized in Sec.V.

II. THEORETICAL MODEL

The hybrid optical and microwave piezo-optomechanical cavity system we proposed is demonstrated in Fig.1(a), which an optomechanical crystal AlN-nanobeam resonator is placed in a planar superconducting microwave cavity contactlessly, and Fig.1(b) is the cross-sectional view for the experimental configuration schematic. The optomechanical crystal cavity AlN-nanobeam resonator is a mechanically suspended beam of AlN with an array of period elliptical air holes are patterned, which is designed to support the highly localized phonon mode and the co-localized optical mode simultaneously, and the same structure has already been designed and applied in the related experiment [7]. The high quality planar superconducting microwave cavity is an LC resonator consisted by superconductive inductors and parallel capacitor plates, thus it should be conducted at low temperature experimentally [35]. The planar superconducting microwave cavity is placed over the optomechanical crystal AlN-nanobeam resonator via the optical waveguide. The AlN-nanobeam mechanical resonator can be effectively driven by both the microwave field via the piezoelectric interaction and the optical field via the radiation pressure, with the coupling between the optical field and the mechanical motion is refereed as the optomechanical coupling, and the coupling between the microwave field and the mechanical motion is refereed as the piezomechanical coupling.

We assume that a strong pump field with frequency $\omega_{pu}$ and a weak probe field with frequency $\omega_{pr}$ are applied to the optomechanical AlN-nanobeam resonator through the optical waveguide, simultaneously a strong
microwave field with frequency \( \omega_k \) is applied to the planar superconducting microwave cavity. The localized optical cavity mode and co-localized phonon mode of the AlN-nanobeam resonator are represented by the photon operators \( \hat{a}(\hat{a}^\dagger) \) and the mechanical phonon operators \( \hat{b}(\hat{b}^\dagger) \), with the frequencies of them are \( \omega_a \) and \( \omega_b \) respectively. The microwave cavity mode is represented by the photon operators \( \hat{c}(\hat{c}^\dagger) \), with the frequency is \( \omega_c \).

By adopting the interaction picture with respect to \( H' = \hbar\omega_{pa}\hat{a}^\dagger\hat{a} + \hbar\omega_{pc}\hat{c}^\dagger\hat{c} \), the total Hamiltonian of the integrated system is given by:

\[
H = H_0 + H_1,
\]

where

\[
H_0 = \hbar\Delta_a\hat{a}^\dagger\hat{a} + \hbar\Delta_c\hat{c}^\dagger\hat{c} + \omega_b\hat{b}^\dagger\hat{b},
\]

\[
H_1 = -\hbar g_{om}\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b}) - \hbar g_{em}(\hat{b}\hat{c}^\dagger + \hat{b}^\dagger\hat{c})
+ (i\hbar\varepsilon_{pu}\hat{a}^\dagger(\hat{b}^\dagger + \hat{b})
+ i\hbar\varepsilon_{pr}e^{-i\delta_a}\hat{a}^\dagger + i\hbar\varepsilon_{k}\hat{c}^\dagger + H.c.).
\]

\( H_0 \) is the free Hamiltonian of the system, with \( \Delta_a = \omega_a - \omega_{pa}, \Delta_c = \omega_c - \omega_{pc} \), the three terms of it are the energies of the optical cavity mode, the microwave cavity mode and the mechanical phonon mode in sequence. \( H_1 \) is the free Hamiltonian of the system, the first term of it is the usual optomechanical interaction term with the optomechanical interaction strength \( g_{om} \), \( g_{om} \) is referred as single-photon coupling strength, which is defined as \( g_{om} = \sqrt{\hbar/m}\omega_b \), with \( m \) is the effective mass of mechanical mode and \( L \) is the effective length of the optical Fabry-Perot cavity. The second term of \( H_1 \) represents the microwave field actuation of the mechanical phonon mode, using a Jaynes–Cummings interaction with the piezomechanical coupling strength is \( g_{em} \), which can be designed exceeding strong coupling region. The last four terms of \( H_1 \) describe the Hamiltonian of the injecting fields, with \( \delta = \omega_{pr} - \omega_{pu} \), where \( \varepsilon_{pu}, \varepsilon_{pr}, \) and \( \varepsilon_k \) are the intensity of the input optical pump field, optical probe field, and the microwave field respectively, they are defined as \( \varepsilon_{pu} = \sqrt{P_{pu}\kappa_a/\hbar\omega_{pu}}, \varepsilon_{pr} = \sqrt{P_{pr}\kappa_a/\hbar\omega_{pr}} \) and \( \varepsilon_k = \sqrt{P_k\kappa_c/\hbar\omega_k} \), with \( P_{pu}, P_{pr}, \) and \( P_k \) are the input powers of the optical pump field, optical probe field, and the microwave field. \( \kappa_a \) and \( \kappa_c \) are the decay rates of the optical cavity and the microwave cavity respectively.

Using the Heisenberg equations of motion and neglecting the quantum fluctuation effects of the environment [32], the resulting nonlinear Langevin equations for the operators of the optical field mode, microwave field mode and the mechanical mode can be written as:

\[
\dot{a} = -(i\Delta_a + \frac{\kappa_a}{2})a + ig_{om}a(b^\dagger + b) + \varepsilon_{pu} + \varepsilon_{pr}e^{-i\delta_a},
\]

\[
\dot{b} = -(i\Delta_b + \frac{\kappa_b}{2})b + ig_{om}a^\dagger a + ig_{em}c + \varepsilon_k,
\]

\[
\dot{c} = -(i\Delta_c + \frac{\kappa_c}{2})c + ig_{em}b + \varepsilon_k,
\]

\[
b = -(i\omega_b + \frac{\gamma_b}{2})b + ig_{om}a^\dagger a + ig_{em}c,
\]

with \( \gamma_b \) is the intrinsic mechanical damping rate of resonator \( b \), and the hat symbol of the operator is omitted for simplicity.

As the optical probe field is a weak field compared to the optical pump field and the microwave field, with the intensities satisfy the conditions \( \varepsilon_{pr} \ll \varepsilon_{pu} \) and \( \varepsilon_{pr} \ll \varepsilon_k \), we can linearize the dynamical equations of the system by assuming \( a = a_s + \delta a, c = c_s + \delta c \) and \( b = b_s + \delta b \), which all of them are composed of a average amplitude and a fluctuation term. Here \( a_s, c_s \) and \( b_s \) are steady-state values when only considering the strong optical pump field and the microwave field is applied, by assuming \( \varepsilon_{pr} \rightarrow 0 \) and all time derivatives vanished, they can be gotten as:

\[
a_s = \frac{\varepsilon_{pu}}{i\Delta_a + \frac{\kappa_a}{2}},
\]

\[
c_s = \frac{ig_{em}b_s + \varepsilon_k}{i\Delta_c + \frac{\kappa_c}{2}},
\]

\[
b_s = \frac{ig_{om}|a_s|^2 + ig_{em}c_s}{i\omega_b + \frac{\gamma_b}{2}},
\]

where \( \Delta'_a = \Delta_a - g_{om}(b_s^\dagger + b_s) \), \( \Delta'_c = \Delta_c - g_{em}(c_s^\dagger + c_s) \). The equations into another interaction picture by introducing \( \delta a = \delta a e^{-i\delta t}, \delta c = \delta c e^{-i\delta t}, \delta b = \delta b e^{-i\delta t} \), with ignoring the fast oscillating terms \( e^{i\delta t} \), the following equations can be obtained:
\[ \delta a = (i\lambda_a - \frac{\kappa_a}{2})\delta a + iG_{om}\delta b + \varepsilon_{pr}, \quad (13) \]

\[ \delta c = (i\lambda_c - \frac{\kappa_c}{2})\delta c + ig_{em}\delta b, \quad (14) \]

\[ \delta b = (i\lambda_b - \frac{\gamma_b}{2})\delta b + iG_{om}\delta a + ig_{em}\delta c, \quad (15) \]

where \( \lambda_a = \delta - \Delta'_a, \lambda_c = \delta - \Delta_c, \lambda_b = \delta - \omega_b. \)

Under the steady-state condition \( \langle \delta a \rangle = \langle \delta c \rangle = \langle \delta b \rangle = 0, \) which is:

\[ 0 = (i\lambda_a - \frac{\kappa_a}{2})\langle \delta a \rangle + iG_{om}\langle \delta b \rangle + \varepsilon_{pr}, \quad (16) \]

\[ 0 = (i\lambda_c - \frac{\kappa_c}{2})\langle \delta c \rangle + ig_{em}\langle \delta b \rangle, \quad (17) \]

\[ 0 = (i\lambda_b - \frac{\gamma_b}{2})\langle \delta b \rangle + iG_{om}\langle \delta a \rangle + ig_{em}\langle \delta c \rangle, \quad (18) \]

we can get the solution of \( \langle \delta a \rangle \) which corresponding to the intracavity field oscillating at the optical probe frequency:

\[ \delta a = \frac{\varepsilon_{pr}}{\frac{\varepsilon_{pr}}{\Delta a} - i\lambda_a + \frac{|G_{om}|^2}{\frac{\varepsilon_{pr}}{\Delta a} - i\lambda_a + \frac{\pi\varepsilon_{pr}}{\Delta a} - i\lambda_c}}. \quad (19) \]

With the input-output relation of the cavity, the output fields at the probe frequency can be expressed as [33, 40]

\[ \varepsilon_{out}(t) = 2\kappa_a\delta a - \varepsilon_{pr}, \quad (20) \]

the transmission coefficient of the probe field can be further defined as:

\[ \varepsilon_T = \frac{\varepsilon_{out}(t)/\varepsilon_{pr} + 1}{\varepsilon_{pr}} = \frac{2\kappa_a}{\frac{\varepsilon_{pr}}{\Delta a} - i\lambda_a + \frac{|G_{om}|^2}{\frac{\varepsilon_{pr}}{\Delta a} - i\lambda_a + \frac{\pi\varepsilon_{pr}}{\Delta a} - i\lambda_c}}, \quad (21) \]

yields the real and imaginary parts, with the real part \( Re[\varepsilon_T] \) and imaginary part \( Im[\varepsilon_T] \) describe the absorption and dispersion of the system respectively.

Supposing that both the optical cavity and the microwave cavity are driven at the mechanical red sideband with \( \Delta'_a = \Delta_c = \omega_b, \) define \( \lambda = \lambda_a = \lambda_c = \lambda_b, \) after some simplification, the term \( \varepsilon_T \) can be written in a more intuitive form

\[ \varepsilon_T = \frac{2\kappa_a}{\frac{\varepsilon_{pr}}{\Delta a} - i\lambda + \frac{A_+}{\lambda_+ - i\lambda} + \frac{A_-}{\lambda_- - i\lambda}}, \quad (22) \]

FIG. 2. (color online) (a) The absorption \( Re[\varepsilon_T] \) and (b) the dispersion \( Im[\varepsilon_T] \) as function of \( (\delta - \omega_b)/\omega_b. \) With the parameters \( g_{om}/2\pi = 1.1 \text{ MHz}, \) \( g_{em}/2\pi = 40 \text{ MHz}, \) \( \kappa_a/2\pi = 5.3 \text{ GHz}, \) \( \kappa_c/2\pi = 0.27 \text{ MHz}, \) \( \gamma_b/2\pi = 0.096 \text{ MHz}, \) \( \omega_a/2\pi = 194 \text{ THz}, \) \( \omega_c/2\pi = 10 \text{ GHz}, \) \( \omega_b/2\pi = 2.4 \text{ GHz}, \) \( \varepsilon_{pr} = 0.12 \text{ mW}, \) \( \varepsilon_b = 0.1 \text{ mW}, \) and \( \Delta_a = \Delta_c = \omega_b, \) it has a standard form for the double-OMIT, which is similar to the double-EIT [41], with \( \lambda_{\pm} \) and \( A_{\pm} \) are

\[ \lambda_{\pm} = \frac{\gamma_b + \kappa_b}{2} \pm i \sqrt{4 g_{em}^2 - \left( \frac{\gamma_b - \kappa_b}{2} \right)^2}, \quad (23) \]

\[ A_{\pm} = \pm \frac{\lambda_{\pm} - \gamma_b}{\lambda_+ - \lambda_-} |G_{om}|^2. \quad (24) \]

III. PHYSICS MECHANISM OF THE DOUBLE-OMIT

We present below is the feasibility of double-OMIT in the hybrid piezo-optomechanical cavity system, the parameters of the optomechanical crystal AlN-nanobeam resonator we used are based on the realistic system [9], with the single photon optomechanical coupling strength can exceeding \( g_{om}/2\pi = 1.1 \text{ MHz}, \) Similarly, the parameters of the planar superconducting microwave cavity and the piezomechanical coupling strength we used are also based on the related experiments, with the intrinsic quality factor of the planar superconducting microwave cavity can exceeding \( 4 \times 10^4 \) [35], and the piezomechanical coupling strength \( g_{em}/2\pi = 40 \text{ MHz} \) has been realized [37].

As is shown in FIG. 2, the absorption \( Re[\varepsilon_T] \) and dispersion \( Im[\varepsilon_T] \) of the optical probe field are plotted as function of \( (\delta - \omega_b)/\omega_b, \) under the condition that both the optical cavity and the microwave cavity are driven at the mechanical red sideband with \( \Delta'_a = \Delta_c = \omega_b. \) The absorption line of the optical probe field presents two dips.
FIG. 3. (color online) (a) The absorption $\text{Re}[\epsilon_T]$ and (b) the dispersion $\text{Im}[\epsilon_T]$ as function of $(\delta - \omega_b)/\omega_b$ without the piezomechanical coupling, i.e., $g_{em} = 0$. The other parameters are the same as in Fig. 2.

which corresponds to the double-OMIT behavior, and the positions of the dips are determined by the imaginary part of $\lambda_\pm$, as is shown in Eq. [23], which is closely related to the piezomechanical coupling strength $g_{em}$. If we diminish the piezomechanical coupling strength, the form of the $\epsilon_T$ becomes:

$$\epsilon_T = \frac{2\kappa_a}{\omega_a - i\lambda_a + |G_{om}|^2},$$

it has the standard form of the single OMIT window, as is shown in FIG. 3.

The origin of the double-OMIT can be explained by the quantum interference effect between different energy level pathways, and the energy level configuration is presented in Fig. 4 (a). In the hybrid piezo-optomechanical cavity system, a N-type four-level system can be formed by the energy level of the superconducting microwave cavity, the optical cavity and the mechanical resonator. With the corresponding driving of optical field and the microwave field applied to different levels, the energy level of the mechanical resonator is split into two new dressed levels by the piezomechanical coupling effect, under the condition $\Delta'_a = \Delta_c = \omega_b$ for simplicity, the two new dressed levels are $\lambda_\pm$ with the disparity $2g_{em}$, as is shown in the dressed-state picture Fig. 4 (b). Then the third-order nonlinear absorption can be enhanced by constructive quantum pathway interference while the linear absorption is inhibited by destructive quantum pathway interference, as the result, the single OMIT window is replaced by the double-OMIT window, and the relevant mechanisms have been studied extensively [38, 39]. More importantly, as the transmission depth and width of double transparency window can be controlled by both the pumped optical field and the stimulated microwave field, our scheme can also be applied to control the optical information processing with the microwave field.

IV. TUNABLE DOUBLE-OMIT BY THE OPTICAL AND MICROWAVE FIELD

To future explore the characteristic of the microwave controlled optical double-OMIT, we plot the absorption $\text{Re}[\epsilon_T]$ as functions of $(\delta - \omega_b)/\omega_b$ and $g_{em}$ in FIG. 5. It is shown that in the absence of the controlled microwave field, the transmission spectrum of the optical probe field
is appeared as a single transparency window, which is induced by the optomechanical coupling when the optical pump field strength is strong enough. With the enhancement power of the controlled microwave field applied to the mechanical resonator, the single transmission window is split into the two transparency window, and the disparity between the two dips is also gradually becoming larger, which is determined by the piezomechanical coupling strength $g_{om}$. This phenomenon can be used to realize the coherent population trapping of the photons or optical switch, which is controlled via the microwave field is applied of not.

FIG. 6 presents the variation of the absorption $Re[e_{T}]$ with respect to $(\delta - \omega_b)/\omega_b$ for different strength of the optical pump field. We find that in the absence of the optical pump field, even though the microwave field which can generate the strong piezomechanical coupling is applied, no transmission spectrum of the optical probe field appeared, the reason is that there is no quantum interference between the energy level pathways occurs. With the enhancing power of the optical pump field, the transmission depth of the double-OMIT window which is determined by the optomechanical coupling strength $G_{om}$ is increased. This phenomenon can be used to control the transmission flux of the optical probe field by the optical pump control field.

Furthermore, we discuss the absorption of the double-OMIT when the frequency detuning $\Delta_c$ between the microwave driven field and the superconducting microwave cavity is different with the mechanical resonator. As is illustrated in FIG. 7, when the detuning $\Delta_c$ is far away from the frequency of the mechanical resonator $\omega_b$, there is no double-OMIT appears. When the detuning $\Delta_c$ is slightly different from the $\omega_b$, the double-OMIT window split by the piezomechanical coupling will be asymmetrical, compared with the case of $\Delta_c = \omega_b$, the absorption curves will move rightward or leftward in the case of $\Delta_c < \omega_b$ or $\Delta_c > \omega_b$. The reason is that based on the equations (7)-(9), when $\Delta_c \neq \omega_b$, then the detuning $\Delta'_c$ will be different from the frequency $\omega_b$, and the condition $\lambda_a = \lambda_c = \lambda_b$ will convert into $\lambda_a \neq \lambda_c \neq \lambda_b$, as a result, the symmetrical double-OMIT window will become asymmetrically.

To be more comprehensive, we consider the condition that the frequency of the microwave driven field is resonated with the superconducting microwave cavity, which the detuning $\Delta_c = 0$. FIG. 8 shows that when $\Delta_c = 0$, at the presence of a weak controlled microwave field, there is a extremely tiny sideband appeared at the frequency $\omega_b$, with the enhancement of the controlled microwave field power, the tiny sideband will be disappeared, and the single transmission window will also turn into a narrowband. This is also because that when $\Delta_c = 0$, based on the equations (7)-(9), the steady-state microwave photon value $c_a$ will be modulated prominently by the gradual enhancement of the controlled microwave field strength, and the steady-state phonon number value $b_a$ will also be changed remarkably, then the $\Delta'_a$ will turn to be far from the frequency $\omega_b$, as a result, the transmission window will be minished to a narrowband.

V. CONCLUSION

In conclusion, we proposed a scheme that is able to generate the microwave controlled optical double-OMIT in a hybrid piezo-optomechanical cavity system, which a piezoelectric optomechanical crystal AlN-nanobeam resonator is placed in a superconducting microwave cavity.
The mechanism is that a N-type four-level system can be formed by the system, when the corresponding fields are applied to the system, the energy level of the mechanical resonator is split into two new dressed levels by the piezomechanical coupling effect, then the third-order nonlinear absorption is enhanced by constructive quantum interference while the linear absorption is inhibited by destructive interference, as a result, a double-OMIT window can be generated. Similar to the double-EIT, the scheme we proposed has provided a feasible way which can be used to control the optical field with the microwave field, such as the high-speed optical switches, high-resolution spectroscopy, coherent population trapping or quantum information processing. With the development of the nano-fabrication technology, our scheme can also be expanded to many other solid state quantum systems.

ACKNOWLEDGMENTS

This work is supported by the Strategic Priority Research Program (No. XDB01010200) and the Hundred Talents Program of the Chinese Academy of Sciences (No. Y321311401), and National Natural Sciences Foundation of China (No. 11347147).

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