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基于量子点相干光学谱的马约拉纳费米子探测

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摘 要:研究了半导体纳米线/超导体复合结构中的马约拉纳费米子的存在情况,提出一种用相干光学谱探测马约拉纳费米子的全光学方法.将一束较强的泵浦激光和一束较弱的探测激光同时作用于半导体量子点,由系统的哈密顿量导出半导体量子点的相干光学谱.数值模拟结果表明,相干光学谱中呈现出由半导体量子点与马约拉纳费米子耦合诱导的明确的马约拉纳费米子迹象.半导体量子点与马约拉纳费米子之间的无接触性,避免了探测中杂质信号的引入.半导体量子点与马约拉纳费米子间的耦合强度和探测吸收谱中两尖峰之间的分裂宽度呈正比,可通过测量分裂宽度获得耦合强度,为耦合强度的确定提供了直观的测量方法.

关键词:量子光学;光电子学;光学泵浦-探测;马约拉纳费米子;量子点
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Majorana Fermions Detection Based on the Coherent Optical Spectrum of a Quantum Dot

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Abstract: The existence of Majorana fermions in hybrid semiconductor/superconductor heterostructures was studied, and an all-optical method to probe the Majorana fermions by using coherent optical spectra was presented. A strong pump laser and a weak probe laser were acted on semiconductor quantum dot, and the coherent optical spectra were derived by the Hamiltonian of system. The numerical results indicate that the coherent optical spectra present a distinct signature of the coupling between the semiconductor quantum dot and the Majorana fermions in the optical detection method. The characteristic of non-contact between the semiconductor quantum dot and the Majorana fermions can make the detection process avoid introducing noises. The coupling strength between the semiconductor quantum dot and the Majorana fermions is proportional to the distance of two the peaks in the probe absorption spectrum, so that the coupling strength can be obtained by measuring the distance of two the peaks, which presents a straight forward means to determine the coupling strength.

Key words: Quantum optics; Optoelectronics; Optical pump-probe; Majorana fermions; Quantum dot
OCIS Codes: 270.0270; 250.5590; 300.6420

0 Introduction

Majorana Fermions (MFs)[1-3], although proposed originally as a model for neutrinos[4-6], have been discovered in condensed matter systems[7-10], especially predicted to exist in hybrid topological insulators/superconductors structure theoretically[11-12]. Due to their potential applications in decoherence-free quantum computation, MFs have attracted a great deal of attention recently. Over the recent few years, the possibility for realizing MFs in exotic solid state systems has paved the way in the condensed matter

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community both on theoretical schemes[13-14] and experimental setups[1-4]. One of the most promising candidate schemes for MFs is 1D Semiconducting Nanowire (SNW) proximity with a Superconductor (SC) with Rashba Spin-Orbit Interaction (SOI)[1-3], which is anticipated that the MFs may emerge at the end of the nanowire.

Experimental detections of MFs usually adopt the non-quantized zero bias conductance peak[1-3] and the fractional Alternating Current (AC) Josephson effect[4]. Besides, MFs could also be probed via quantum non-locality, transconductance, interference, the noise measurements[15-16], and 4π periodic Majorana Josephson currents[17]. One of remarkable schemes for probing MFs that would manifest as a conductance peak at zero voltage with tunneling spectroscopy[18-20], additionally, the zero-bias anomalies in the hybrid SNW/SC heterostructures devices have been observed experimentally[1-3]. Unfortunately, a zero-bias anomalie might also occur under similar conditions due to a Kondo resonance once the magnetic field has suppressed the superconducting gap enough to permit the screening of a localized spin[21-22]. In the electrical measurement, the noises confused the Majorana signals will also be involved, which will affect the judgment whether the Majorana-like signals are true MFs. How to verify the definite MFs is still challenging. Further, the electrical means will also introduce the electron transfer into or out of MFs via the nanowire, which will destroy the qubits information when MFs are used to quantum computing. It is necessary to seek more definitive signatures of MFs. Recently, the detections of MFs with a single Quantum Dot (QD)[23-26] have been proposed, which provides a potential way to probe MFs without totally destroying the information in the qubits. In addition, a scheme for measuring the lifetime of MFs with a QD in the hybrid SNW/SC heterostructures was also presented with electrical measurements[27]. Further, Nadj-Perge et al[28] have reported the disappearance of edge-localized zero-bias peaks when the underlying superconductivity is suppressed. They provide another evidence to show that the Majorana fermions is associated with superconductivity and not with other phenomena such as the Kondo effect. In order to restrain the Kondo effect, the hybrid SNW/SC devices can be replaced by the new scheme of a chain of Fe atoms fabricated on top of a superconductor Pb substrate to detect MFs.

Here, a method to detect the existence of MFs with a QD in all-optical domain was proposed. As shown in Fig. 1, a SNW contacting with a SC coupled to a QD with optical pump-probe technique[29] is presented to detect Majorana signature via the coherent optical spectra of the QD. Compared with the electrical detection of MFs where the QD is coupled to MF via tunneling[23-24], in the optical scheme, the QD-MF coupling is mainly due to dipole-dipole interaction. As in current experiments the distance between QD and MF can be adjusted to about several tens of nanometers, therefore, the tunneling between the QD and MF can be neglected. The signal change in the coherent optical spectra as a possible signature for the MFs is another potential evidence in the hybrid SNW/SC heterostructures, and the optical scheme will provide another alternative method for the detection of MFs, which is very different from the zero-bias peak in the tunneling experiments[1-3]. Moreover, there is no contact between the QD and the hybrid SNW/SC structure in our scheme, which avoids introducing the noises influencing the detection of Majorana signature, and finally improving the sensitivity of the measurement. Based on the optical means, a straightforward methods for determining the QD-MF coupling strength and the lifetime of the MFs are also proposed.

1 Theory

Fig. 1 shows the schematic setup that will be studied in this work, where a pair of MFs will emerge in the ends of the nanowire in the hybrid SNW/SC heterostructures, and a QD coupled to the nearby MFs. Combining a strong Rashba SOI and Zeeman splitting with the proximity-effectinduced s-wave superconductivity in the nanowire, this hybrid system can experimentally support MFs at the ends of the nanowire[1-2]. As usual, the QD is modeled as a two-level system consisting of the ground state $|g\rangle$ and the single exciton state $|ex\rangle$[30-31] at a low temperature. Thus, the two-level exciton can be characterized by the pesudospin $-1/2$ opterators $S^{\pm}$ and S^{z} with the commutation relation $[S^{z}, S^{\pm}] = \pm S^{\pm}$ and $[S^{+}, S^{-}] = 2S^{z}$.

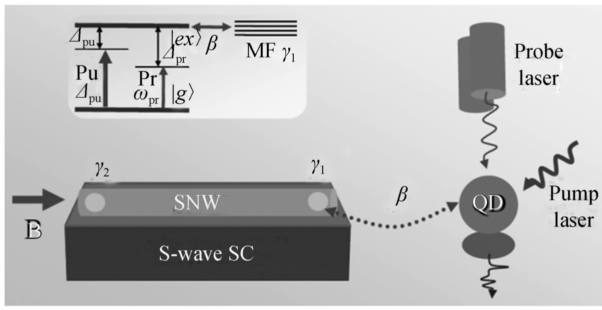


Fig. 1 All-optical detection scheme of MFs via QD with two optical excitons

1.1 The QD-MF coupling

Suppose the QD is coupled to γ_1 as shown in Fig. 1, and the Hamiltonian describing the coupling between MFs the QD is[23-25]

$$H_1=\hbar\omega_D S^z+\mathrm{i}\hbar\omega_M\gamma_1\gamma_2/2+\mathrm{i}\hbar\beta(S^- - S^+)\gamma_1 \quad (1)$$

In order to detect the existence of MFs, it is helpful to switch from the Majorana representation to the regular fermion one through the exact transformation $\gamma_1 = f^+ + f$ and $\gamma_2 = \mathrm{i}(f^+ - f)$, where f and f^+ are the fermion annihilation and creation operators obeying the anti-commutative relation $\{f, f^+\}=1$. Accordingly, H_1 can be rewritten as

$$H_{\mathrm{eff}}=\hbar\omega_D S^z+\hbar\omega_M(f^+f-1/2)+\mathrm{i}\hbar\beta(S^- - S^+)(f^+ - f) \quad (2)$$

where the first term describes the two-level exciton in the QD and ω_D is the exciton frequency. The second term gives the energy of MF at frequency ω_M, where $\hbar\omega_M=\varepsilon_M \sim \mathrm{e}^{-l/\xi}$ with the wire length (l) and the superconducting coherent length (ξ)[23-24]. This term is small and will approach zero when the wire length is big enough. The last term is the QD-MF coupling with the coupling strength β, where the coupling strength is related to the distance between the QD and the hybrid SNW/SC structure.

1.2 The QD-optical field coupling and Hamiltonian of the system

Applying a strong pump field and a weak probe field to the QD simultaneously, the Hamiltonian of the QD coupled to the pump field and probe field[32] is $H_{\mathrm{QD\text{-}F}}=-\mu\sum_{i=\mathrm{pu,pr}}E_i(S^+\mathrm{e}^{-\mathrm{i}\omega_i t}+S^-\mathrm{e}^{\mathrm{i}\omega_i t})$ where μ is the electric dipole moment of the exciton, ω_{pu} and ω_{pr} are the frequency of the pump field and the probe field, and E_{pu}(E_{pr}) is the slowly varying envelope of the pump field (probe field).

In a rotating frame of the frequency ω_{pu}, and neglecting the term of nonconservation, the total Hamiltonian of the system is

$$H=\hbar\Delta_{\mathrm{pu}}S^z+\hbar\Delta_M f^+f+\mathrm{i}\hbar\beta(S^-f^+-S^+f)-\hbar\Omega_{\mathrm{pu}}(S^++S^-)-\mu E_{\mathrm{pr}}(S^+\mathrm{e}^{-\mathrm{i}\delta t}+S^-\mathrm{e}^{\mathrm{i}\delta t}) \quad (3)$$

where $\Delta_{\mathrm{pu}}=\omega_D-\omega_{\mathrm{pu}}$ is the detuning of the exciton frequency and the pump frequency, $\Omega_{\mathrm{pu}}=\mu E_{\mathrm{pu}}/\hbar$ is the Rabi frequency of the pump field, and $\delta=\omega_{\mathrm{pr}}-\omega_{\mathrm{pu}}$ is the probe-pump detuning. $\Delta_M=\omega_M-\omega_{\mathrm{pu}}$ is the detuning of the MF frequency and the pump frequency. Actually, the regular fermion like normal electrons in the nanowire that interact with the QD in the above discuss is neglected. To describe the interaction between the normal electrons and the QD, we introduce the tight binding Hamiltonian of the whole wire as[33] $H_{\mathrm{FS}}=\hbar\omega_D S^z+\hbar\sum_k\omega_k c_k^+c+\hbar g\sum_k(c_k^+S^-+S^+c_k)$, where c_k and c_k^+ are the regular fermion annihilation and creation operators with energy ω_k and momentum k obeying the anticommutative relation $\{c_k, c_k^+\}=1$, and g is the coupling strength between the normal electrons and the QD (here for simplicity we have neglected the k-dependence of g as in Ref. [34]).

1.3 The quantum Langevin equations

According to the Heisenberg equation of motion and introducing the corresponding damping and noise terms, the quantum Langevin equations reads as

$$\dot{S}^z=-\Gamma_1(S^z+1/2)-\beta(S^-f^++S^+f)+\mathrm{i}\Omega_{\mathrm{pu}}(S^+-S^-)+\frac{\mathrm{i}\mu E_{\mathrm{pr}}}{\hbar}(S^+\mathrm{e}^{-\mathrm{i}\delta t}-S^-\mathrm{e}^{\mathrm{i}\delta t}) \quad (4)$$

$$\dot{S}^-=-(\mathrm{i}\Delta_{\mathrm{pu}}+\Gamma_2)S^-+2\beta S^z f-2\mathrm{i}\Omega_{\mathrm{pu}}S^z-\frac{2\mathrm{i}\mu S^z E_{\mathrm{pr}}}{\hbar}\mathrm{e}^{-\mathrm{i}\delta t}+\hat{F}_{\mathrm{in}}(t) \quad (5)$$

$$\dot{f}=-(\mathrm{i}\Delta_M+\kappa_M/2)f+\beta S^-+\hat{\xi}(t) \quad (6)$$

where Γ_1 is the exciton relaxation rate, Γ_2 is the exciton dephasing rate and κ_M is the decay rate of the MF. $\hat{F}_{\mathrm{in}}(t)$ is the δ-correlated Langevin noise operator with zero mean $[\hat{F}_{\mathrm{in}}(t)]=0$ obeying the correlation function $[\hat{F}_{\mathrm{in}}(t)\hat{F}_{\mathrm{in}}^+(t')]\sim\delta(t-t')$. The MF with damping rate κ_M is affected by a viscous force and a Brownian stochastic force with zero mean value, and $\hat{\xi}(t)$ has the correlation function

$$\langle\hat{\xi}^+(t)\hat{\xi}(t')\rangle=\frac{\kappa_M}{\omega_M}\int\frac{\mathrm{d}\omega}{2\pi}\omega\mathrm{e}^{-\mathrm{i}\omega(t-t')}\left[1+\coth\left(\frac{\hbar\omega}{2k_B T}\right)\right] \quad (7)$$

where k_B and T are the Boltzmann constant and the temperature of the reservoir of the coupling system.

To go beyond weak coupling, the Heisenberg operator can be rewritten as the sum of its steady-state mean value and a small fluctuation with zero mean value: $O=O_0+\delta O(O=S^z, S^-, f)$. Since the driving fields are weak while classical coherent fields, we will identify all operators with their expectation values, and drop the quantum and thermal noise terms.

1.4 The coherent optical spectra

Inserting operators into the Langevin equations Eqs. (4)～(6) and neglecting the nonlinear terms, we obtain two sets of equations. The steady-state equation set consisting of f_0 and S_0^- related to the population inversion ($w_0=2S_0^z$) of the exciton is determined by

$$\Gamma_1(w_0+1)[(\beta^2w_0+\Delta_{\mathrm{pu}}\Delta_M)^2+\Gamma_2^2(\Delta_M^2+\kappa_M^2/4)+(\Delta_{\mathrm{pu}}^2\kappa_M^2/4-\beta^2\Gamma_2\kappa_M w_0)]-4\beta^2\Omega_{\mathrm{pu}}^2\kappa_M w_0^2+4\Omega_{\mathrm{pu}}^2w_0\Gamma_2(\Delta_M^2+\kappa_M^2/4)=0 \quad (8)$$

For the equation set of small fluctuation, we make the ansatz[32] $\langle\delta O\rangle=O_+\mathrm{e}^{-\mathrm{i}\delta t}+O_-\mathrm{e}^{\mathrm{i}\delta t}$. Solving the equation set and working to the lowest order in E_{pr} but to all orders in E_{pu}, we obtain the linear optical susceptibility as $\chi_{\mathrm{eff}}^{(1)}(\omega_{\mathrm{pr}})=\mu S_+(\omega_{\mathrm{pr}})/E_{\mathrm{pr}}=\Sigma_1\chi^{(1)}(\omega_{\mathrm{pr}})$ with $\Sigma_1=\mu^2/\hbar\Gamma_2$, and $\chi^{(1)}(\omega_{\mathrm{pr}})$ is given by

$$\chi^{(1)}(\omega_{\mathrm{pr}})=\frac{\mathrm{i}[\Pi S_0^*-w_0(\Gamma_1+\Theta_2\Pi^*/D_1-\mathrm{i}\delta)]\Gamma_2}{D_1(\Gamma_1+\Theta_2\Pi^*/D_1-\mathrm{i}\delta)-\Pi\Theta_1} \quad (9)$$

where $\varphi_1 = \frac{\beta}{[\kappa_M/2+\mathrm{i}(\Delta_M-\delta)]}$, $\varphi_2 = \frac{\beta}{[\kappa_M/2+\mathrm{i}(\Delta_M+\delta)]}$, $\Theta_1 = \mathrm{i}\Omega_{pu} - \beta(f_0^* + S_0^*\varphi_1)$, $\Theta_2 = \mathrm{i}\Omega_{pu}+\beta(f_0+S_0\varphi_2^*)$, $\Theta_3 = \mathrm{i}\Omega_{pu}-\beta(f_0^*+S_0^*\varphi_2)$, $\Theta_4 = \mathrm{i}\Omega_{pu}+\beta(f_0+S_0\varphi_1^*)$, $\Pi = 2(\beta f_0 - \mathrm{i}\Omega_{pu})$, $D_1=\Gamma_2-\beta w_0\varphi_1+\mathrm{i}(\Delta_{pu}-\delta)$, $D_2=\Gamma_2-\beta w_0\varphi_2^*-\mathrm{i}(\Delta_{pu}+\delta)$, $D_3=\Gamma_2-\beta w_0\varphi_2+\mathrm{i}(\Delta_{pu}+\delta)$, $D_4=\Gamma_2-\beta w_0\varphi_1^*+\mathrm{i}(\Delta_{pu}+\delta)$. The imaginary and real parts of $\chi^{(1)}(\omega_{pr})$ indicate absorption and dispersion, respectively.

The nonlinear optical susceptibility is $\chi_{\mathrm{eff}}^{(3)}(\omega_{pr}) = \mu S_-(\omega_{pr})/(2E_{pu}^2 E_{pr}) = \Sigma_3\chi^{(3)}(\omega_{pr})$, where $\Sigma_3 = \mu^4/(3\hbar^3\Gamma_2^3)$, and $\chi^{(3)}(\omega_{pr})$ is given by

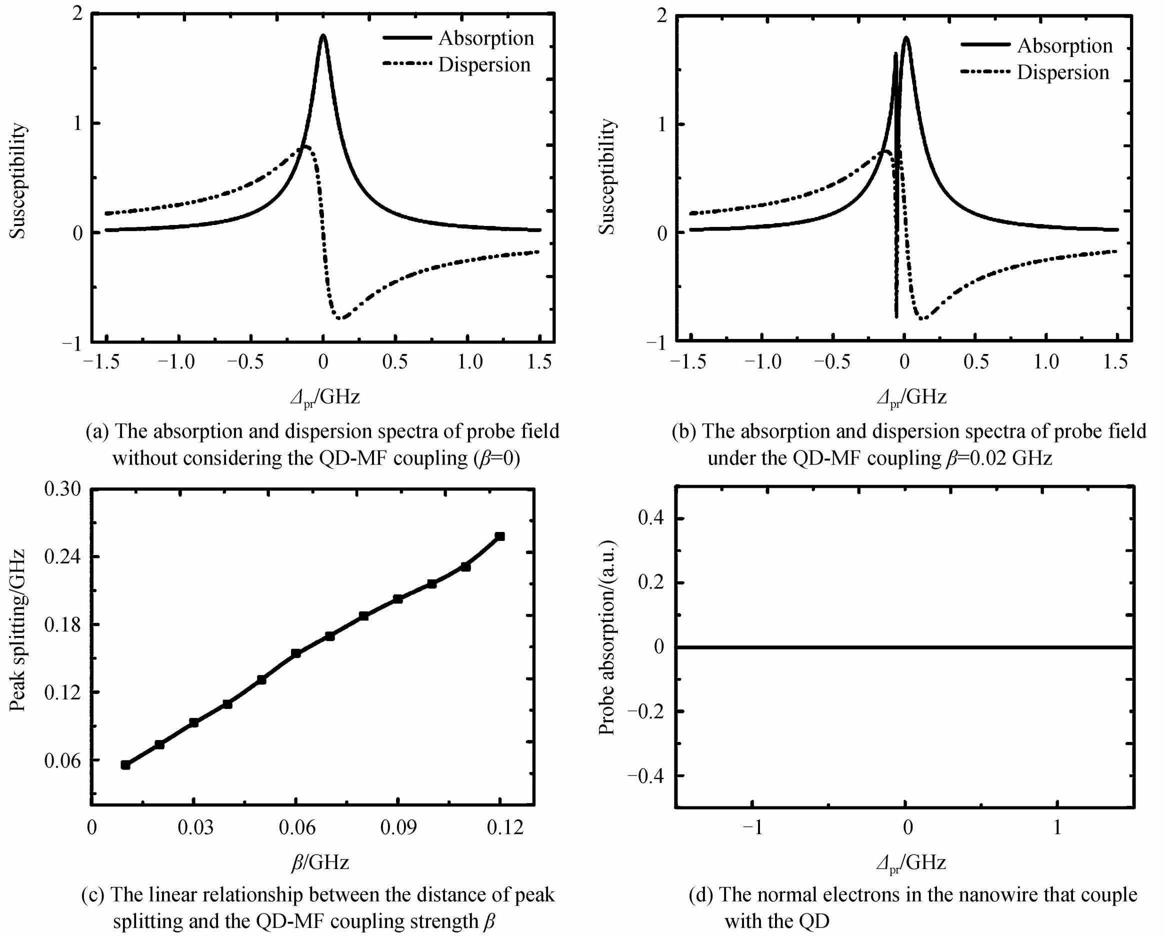
$$\chi^{(3)}(\omega_{pr}) = \frac{\mathrm{i}\Pi(w_0\Theta_4+S_0 D_4)\Gamma_2^3}{[(\Gamma_1+\mathrm{i}\delta)D_3 D_4+\Theta_1 D_3\Pi^* - \Theta_3 D_4\Pi]\Omega_{pu}^2} \tag{10}$$

the real and imaginary parts of $\chi^{(3)}(\omega_{pr})$ characterize the Kerr coefficient and nonlinear absorption, respectively. The quantum Langevin equations of the normal electrons coupled to the QD have the same form as MFs, therefore, we neglect their derivations and only give the results in the following section.

2 Results and discussions

For illustration of the numerical results, we choose the realistic coupled system of an InAs QD[35] coupled to an InSb nanowire [1-3], which is known to have strong spin-orbit interaction and a large g factor. We use the realistic parameters for the QD[35]: $\Gamma_1 = 0.3$ GHz and $\Gamma_2 = \Gamma_1/2$. For MFs, there are no experimental values for the lifetime of the MFs and the coupling strength between QD and MFs as far as we know. According to a few reports[1-4], we expect that the decay rate of the MF is in the range of megahertz and $\kappa_M = 0.1$ MHz. For the coupling strength between the QD and nearby MFs is related to their distance, we expect the coupling strength $\beta = 0.02$ GHz via adjusting the distance between the QD and the hybrid SNW/SC heterostructures. The QD coupled to the nearby MF induces the coupled QD-MF, which produces the coupled states $|ex, n_M\rangle$ and $|ex, n_M+1\rangle$ (n_M denotes the number states of the MFs) as shown in the inset of Fig. 1.

When radiating a strong pump field and a weak probe field on the coupled QD-MF system, the existence of MFs can be probed with the coherent optical spectra. Fig. 2(a) and Fig. 2(b) show the absorption (i. e., the imaginary part of the dimensionless susceptibility Imχ(1)) and dissipation (i. e., the real part of the dimensionless susceptibility



(a) The absorption and dispersion spectra of probe field without considering the QD-MF coupling (β=0)

(b) The absorption and dispersion spectra of probe field under the QD-MF coupling β=0.02 GHz

(c) The linear relationship between the distance of peak splitting and the QD-MF coupling strength β

(d) The normal electrons in the nanowire that couple with the QD

Fig. 2 The absorption and dispersion spectra of probe field as a function of the probe detuning Δ_{pr} under different conditions

Reχ(1)) properties of the QD as a function of the probe detuning Δ_{pr}($\Delta_{pr}=\omega_{pr}\ \hbar\omega_{D}$) without ($\beta=0$) and with ($\beta=0.02$ GHz) considering the QD-MF coupling, respectively. Fig. 2(a) is the result when no MF exists in the nanowire, which indicates the normal absorption and dissipation of the QD. As MFs appears in the ends of the nanowire, the QD will couple to the nearby MFs, which induces the upper level of the state $|ex\rangle$ splits into $|ex, n_{M}\rangle$ and $|ex, n_{M}+1\rangle$. The peaks splitting appear in Fig. 2(b) indicate the definite QD-MFs interaction, which also is an evidence of the existence of MFs in the ends of the nanowire. This is a key result in the present work. Unlike the case for QD tunneling spectroscopy whose peaks conductance fix at $e^2/2\hbar$ with the emergency of MF and at $e^2/\hbar$ for no coupling and for a coupling with a regular fermionic zero mode[23], both the depth and width of the dip in the coherent optical spectrum change continuously by varying the coupling constant. For these two splitting peaks as shown in Fig. 2(b), the left peak signifies the transition from $|g\rangle$ to $|ex, n\hbar_{M}\rangle$ while the right peak corresponds to the transition from $|g\rangle$ to $|ex, n\hbar_{M}+1\rangle$.

With increasing the coupling strength β, the distance of the two peaks in the probe absorption spectrum becomes larger and larger, which obviously reveals the QD-MFs coupling. Moreover, we find that the distance of the splitting is twice times larger than the QD-MFs coupling strength, which provides a concise way to measure the QD-MFs coupling strength in this coupled system. In Fig. 2(c), we give the linear relationship between the distance of the peak splitting and the coupling strength of the QD-MFs. Therefore, the coupling strength can obtain immediately by directly measuring the distance of two peaks in the probe absorption spectrum. To determine this signature is the true MFs that appear in the nanowire, rather than the normal electrons that couple with the QD, we give the numerical results of the normal electrons in the nanowire that couple with the QD as shown in the inset of Fig. 2(d). In order to compare with the Majorana signature, the parameters are chosen the same as MFs parameters. We find that there is no signal in the probe absorption spectrum which means that the splitting in the coherent optical spectrum (Fig. 2(b)) is the true signature of MFs. Therefore, our result here reveals that the splitting in the probe absorption is a real signature of MFs, and the stronger coupling strength introduces the wider and deeper dip.

We further investigate the nonlinear optical susceptibility of the QD as shown in Fig. 3. Fig. 3(a) and Fig. 3(b) shows the Kerr coefficient and nonlinear absorption as function of the probe detuning Δ_{pr}. Compared with Fig. 3(a) ($\beta=0$), it is obvious that when the MFs appear in the ends of the nanowire and coupled with the QD ($\beta=0.01$ GHz), the two sharp peaks will appear in both the optical Kerr spectrum and nonlinear absorption spectrum of the QD. The physical origin of this result is due to the QD-MF coherent interaction, which makes the resonant enhancement of the optical Kerr effect and nonlinear absorption in the QD. This result also implies that the sharp peaks in the nonlinear optical spectrum may be the signature of MFs at the ends of the nanowire. Therefore, one may also utilize the optical Kerr effect of the QD to detect the existence of MFs provided the QD is close enough to the ends of the nanowire.

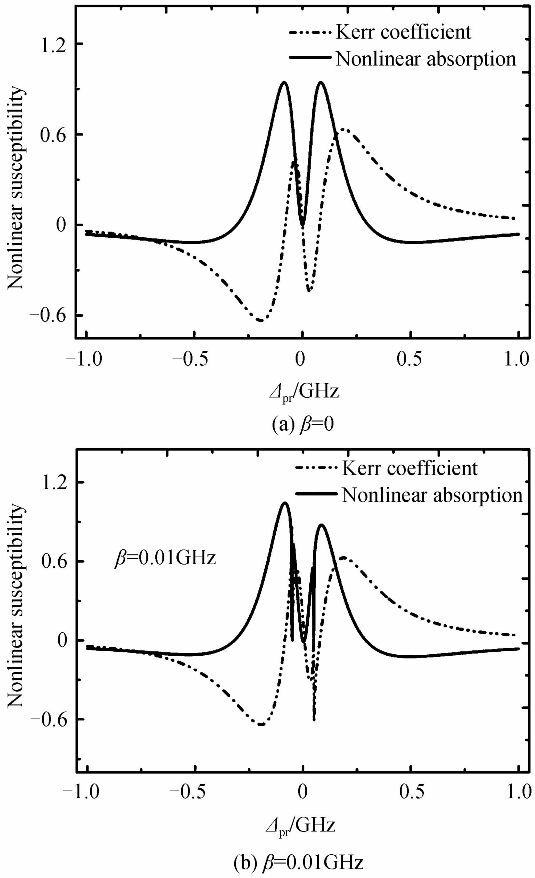


Fig. 3 The optical Kerr coefficient and nonlinear absorption as a function Δ_{pr}

In order to determine the lifetime of the MFs, we plot the relationship between the transmission spectrum and the decay rate of the MFs when the pump field is resonant with the frequency of the exciton as shown in Fig. 4. It shows that the transmission spectrum of the probe beam decreases with increasing of the decay rate of the MFs. This figure can provide us a simple method to measure the decay rate of the MFs via the probe transmission spectrum. Through this method, one can investigate the environmental influences on the MFs via the QD transmission spectrum of the probe field.

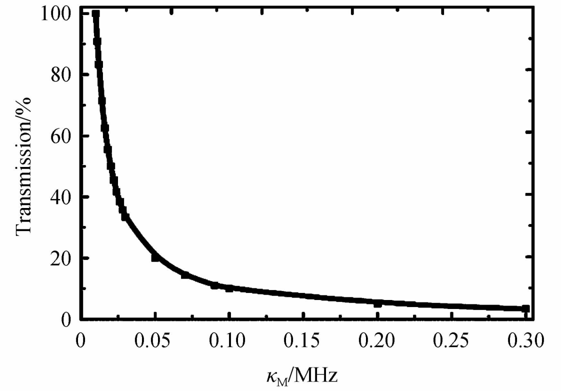


Fig. 4 The transmission spectrum of the probe field as a function of the decay rate of MFs

3 Summary

We have proposed an optical scheme to detect the existence of MFs via a single QD in the hybrid SNW/SC device. The signals in the coherent optical spectra indicate the possible Majorana signature, which provides another supplement for detecting MFs. Based on this coupled system, a method which determines the coupling strength of QD-MFs and the decay rate of the MFs is proposed. In addition, QD is considered as a two-level system rather than a spin-singlet state in our scheme. When the optical pump-probe technology is applied on the QD modeled as a two-level system without considering its spin-singlet state, the detection of Majorana signature will be carried out via the coherent optical spectra.

Compared with electrical measurement, the optical scheme for the detection of MFs have several advantage, the first one is that there is no contact between the QD and the hybrid SNW/SC structure in our scheme, thus the introduce of noises can be avoided effectively, and finally the sensitivity of the measurement will enhance observably. The second one is that nanostructures such as QD have obtained remarkable progress in modern nanoscience, which paves a way to detect MFs experimentally. Therefore, the optical detection of MFs with QD is scientific and feasible based on recent experiment. The scheme proposed here may provide potential applications in all-optically controlled quantum computing based on MFs in hybrid nanostructures.

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