Effects of intrinsic decoherence on various correlations and quantum dense coding in a two superconducting charge qubit system*

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The influence of intrinsic decoherence on various correlations and dense coding in a model which consists of two identical superconducting charge qubits coupled by a fixed capacitor is investigated. The results show that, despite the intrinsic decoherence, the correlations as well as the dense coding channel capacity can be effectively increased via the combination of system parameters, i.e., the mutual coupling energy between the two charge qubits is larger than the Josephson energy of the qubit. The bigger the difference between them is, the better the effect is.

Keywords: superconducting charge qubit, quantum dense coding, channel capacity, intrinsic decoherence

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1. Introduction

Quantum teleportation, quantum key distribution, quantum dense coding, and quantum secret sharing are foundational schemes for quantum communication, which have been presented in different quantum physical systems.[1–7] It is commonly believed that the entanglement which is a nonclassical and nonlocal correlation, is responsible for these possibilities. Wootters[8] introduced the concurrence (C) to calculate the entanglement of two-qubit system. In addition, there are other quantum correlations, which have been discussed widely and found to be useful in some quantum information applications. Quantum discord (QD) is one among them,[9,10] which measures a more general type of quantum correlation and is found to have nonzero values even for separable mixed states. Generally, it is somewhat difficult to calculate QD and the analytical solutions can be hardly obtained except for some particular cases, such as the so-called X states.[11] Some research showed that the QD, C, and classical correlation (CC) are independent measurements of correlations with no simple ordering, and QD is more practical than entanglement.[12] Moreover, Dakić *et al*. have introduced an easily analytically computable quantity, geometrical measurement of quantum discord (GQD),[13] and have given a necessary and sufficient condition for the existence of nonzero QD for any dimensional bipartite states. However, real quantum systems will unavoidably be influenced by the surrounding environment, which leads to decoherence. Although the dynamical behavior of QD is studied in terms of decoherence[14–16] in both Markovian[17] and non-Markovian[18–20] cases, the influence of intrinsic decoherence on various correlations is seldom discussed.[21]

Quantum dense coding, as a fascinating feature of quantum information, has been one of the hot topics since its first proposition by Bennett and Wiesner.[4] In the original protocol, two bits of classical information can be transmitted by sending only one qubit if the two parties share a two-qubit maximally entangled state (EPR state). From then on, piles of works on dense coding have been presented theoretically and experimentally. In 1996, Mattle *et al.*[22] experimentally demonstrated quantum dense coding with two polarized and entangled photons.

In recent years, there have been many reports about the superconducting quantum circuits that have been used in quantum information science.[23–26] This is due to the fact that compared with the other physical systems that have been suggested as possible approaches to realize qubits, the superconducting circuits are more easily embedded in electronic circuits and scaled up to larger registers.[27] Particularly, the charge qubit as one of the basic elements, which can be conveniently addressed by the external parameters, such as gate voltages and magnetic fluxes, has attracted considerable attention in the past decade.[28–30] Many studies about the entanglement properties of the superconducting-charge-qubit system have been done.[30–35] For example, reference [31] discussed the entanglement property of the model, which is composed of two coupled superconducting charge qubits by connecting a large Josephson junction; reference [33] studied the creation and evolution of quantum entanglement in two charge qubits coupled by a nanomechanical resonator system. It was indicated in Ref. [34] that the maximum value of concurrence of two identical charge qubits is much larger than two different

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charge qubits coupled by a fixed capacitor. The entanglement of two charge qubits produced in a damped cavity has also been reported.[36]

In this paper, based on the outline presented above, we will discuss the influence of intrinsic decoherence on various correlations and dense coding in the model of two superconducting charge qubits coupled by a fixed capacitor. The joint effects of intrinsic decoherence, the Josephson energy, and the mutual coupling energy between the two charge qubits on various correlations and dense coding are investigated. Our concern with the interplay between the intrinsic decoherence and system parameters for the correlation dynamics and dense coding will help us clarify the possibilities of fighting against the phase decoherence in increasing the correlations and implementing high quality dense coding.

This paper is organized as follows. In Section 2, we introduce the model and the definitions of correlations. In Section 3, we study the influence of intrinsic decoherence on various correlations of the model. In Section 4, the dense coding of the model under intrinsic decoherence is investigated. Finally, a brief conclusion is made in Section 5.

2. Model and description of various correlations

A superconducting charge qubit is composed of a Cooper-pair box, a tunnel Josephson junction and a superconducting electrode, in which the charge energy ($E_{\rm C}$) dominates the Josephson energy ($E_{\rm J}$). In order to control the interactions between two charge qubits, one possibility is to connect them via a capacitor which allows an easy realization of a CNOT gate.[27] The Hamiltonian for this kind of interaction is an Ising-type coupling term $\sigma_z \otimes \sigma_z$ and the thermal entanglement of this system has been reported.[34] Then, one can write the Hamiltonian of the two superconducting charge qubits system as

$$\begin{aligned} H = & -\frac{1}{2}\left\{\left[4E_{\rm C1}\left(\frac{1}{2}-n_{\rm g1}\right)+2E_{\rm m}\left(\frac{1}{2}-n_{\rm g2}\right)\right]\sigma_{z1}\right. \\ & +\left[4E_{\rm C2}\left(\frac{1}{2}-n_{\rm g2}\right)+2E_{\rm m}\left(\frac{1}{2}-n_{\rm g1}\right)\right]\sigma_{z2} \\ & \left.+E_{\rm J1}\sigma_{x1}+E_{\rm J2}\sigma_{x2}-2E_{\rm m}\sigma_{zz}\right\}, \end{aligned} \tag{1}$$

where $E_{{\rm C}i}$ and $E_{{\rm J}i}$ are the charging and Josephson energy of the i-th charge qubit, respectively; $E_{\rm m}$ is the mutual coupling energy between the two qubits; $\sigma_{x1} = \sigma_x \otimes I$, $\sigma_{x2} = I \otimes \sigma_x$, $\sigma_{z1} = \sigma_z \otimes I$, $\sigma_{z2} = I \otimes \sigma_z$, $\sigma_{zz} = \sigma_z \otimes \sigma_z$, in which σ_x and σ_z are the normal Pauli matrices and I is the identity matrix; $n_{{\rm g}i} = C_{{\rm g}i}V_{{\rm g}i}/2e$ is the normalized qubit gate charge, where $C_{{\rm g}i}$ and $V_{{\rm g}i}$ are the control gate capacitance and voltage, respectively. We consider a simple but nontrivial form of Eq. (1), where $n_{\rm g1} = n_{\rm g2} = 1/2$, i.e., the degeneracy point, which is the condition of insensitivity to fluctuations in the external parameters.[37] Under this condition, the model Hamiltonian is reduced to

$$H = -\frac{1}{2}(E_{\rm J1}\sigma_{x1} + E_{\rm J2}\sigma_{x2} - 2E_{\rm m}\sigma_{zz}), \tag{2}$$

which can be written in the matrix form on the standard basis as

$$\boldsymbol{H} = -\frac{1}{2}\begin{pmatrix} -2E_{\rm m} & E_{\rm J2} & E_{\rm J1} & 0 \\ E_{\rm J2} & 2E_{\rm m} & 0 & E_{\rm J2} \\ E_{\rm J1} & 0 & 2E_{\rm m} & E_{\rm J1} \\ 0 & E_{\rm J2} & E_{\rm J1} & -2E_{\rm m} \end{pmatrix}. \tag{3}$$

We can see that the Hamiltonian is independent of the charging energy $E_{\rm C}$ in this case. Due to the fact that the entanglement resource as well as the quantum discord between two identical charge qubits is much richer than that of different qubits,[36,38] we will focus on the case of qubits with the same system parameters, i.e., $E_{\rm J1} = E_{\rm J2} = E_{\rm J}$ and $E_{\rm C1} = E_{\rm C2}$. The model Hamiltonian can then be rewritten as

$$\boldsymbol{H} = -\frac{1}{2}\begin{pmatrix} -2E_{\rm m} & E_{\rm J} & E_{\rm J} & 0 \\ E_{\rm J} & 2E_{\rm m} & 0 & E_{\rm J} \\ E_{\rm J} & 0 & 2E_{\rm m} & E_{\rm J} \\ 0 & E_{\rm J} & E_{\rm J} & -2E_{\rm m} \end{pmatrix}, \tag{4}$$

where $E_{\rm J}$ and $E_{\rm m}$ can be adjusted by the experimental multiplexed capacitance in the circuits.

Let us now recall the original definitions of QD, CC, C, and GQD. In the classical information theory, the total correlation in a bipartite quantum system (A) and (B), measured by the quantum mutual information, is defined as

$$\mathscr{I}(\rho_{\rm A};\rho_{\rm B}) = S(\rho_{\rm A}) + S(\rho_{\rm B}) - S(\rho_{\rm AB}), \tag{5}$$

where $\rho_{\rm A(B)} = {\rm Tr}_{\rm B(A)}(\rho_{\rm AB})$ is the reduced density matrix of the subsystem A(B) by tracing out the subsystem B(A). The quantum generalization of the conditional entropy is not the simple replacement of Shannon entropy with von Neumann entropy, but through the process of projective measurement on the subsystem B by a set of complete projectors B_k, with the outcomes labeled by k, then the conditional density matrix ρ_k becomes

$$\rho_k = \frac{1}{p_k}(I_{\rm A} \otimes B_k)\rho(I_{\rm A} \otimes B_k), \tag{6}$$

which is the local post-measurement state of the subsystem B after obtaining the outcome k on the subsystem A with the probability

$$p_k = {\rm Tr}[(I_{\rm A} \otimes B_k)\rho(I_{\rm A} \otimes B_k)], \tag{7}$$

where $I_{\rm A}$ is the identity operator on the subsystem A. The projectors B_k can be parameterized as $B_k = V|k\rangle\langle k|V^\dagger$, $k = 0, 1$ and the transform matrix $\boldsymbol{V} \in \boldsymbol{U}(2)$ (in Ref. [39]) is

$$\boldsymbol{V} = \begin{pmatrix} \cos\theta & {\rm e}^{-{\rm i}\phi}\sin\theta \\ -{\rm e}^{{\rm i}\phi}\sin\theta & \cos\theta \end{pmatrix}. \tag{8}$$

Then the conditional von Neumann entropy (quantum conditional entropy) and quantum extension of the mutual information can be defined as[9]

$$S(\rho_{\rm AB}|\{B_k\}) = \sum_k p_k S(\rho_k). \tag{9}$$

Following the definition of the $\mathrm{CC}(\rho_{\rm AB})$[9]

$$\mathrm{CC}(\rho_{\rm AB}) = \sup_{\{B_k\}}\{S(\rho_{\rm A}(t)) - S(\rho_{\rm AB}(t)|\{B_k\})\}. \tag{10}$$

Then $\mathrm{QD}(\rho_{\rm AB})$ defined by the difference between the quantum mutual information $I(\rho_{\rm AB})$ and the $\mathrm{CC}(\rho_{\rm AB})$ is given by $\mathrm{QD}(\rho_{\rm AB}) = I(\rho_{\rm AB}) - \mathrm{CC}(\rho_{\rm AB})$. Then a variant expression of $\mathrm{CC}(\rho_{\rm AB})$ and $\mathrm{QD}(\rho_{\rm AB})$ is given by [9,10]

$$\mathrm{CC}(\rho_{\rm AB}) = S(\rho_{\rm A}) - \min_{\{B_k\}} S(\rho_{\rm AB}|\{B_k\}), \tag{11}$$

$$\mathrm{QD}(\rho_{\rm AB}) = S(\rho_{\rm B}) - S(\rho_{\rm AB}) + \min_{\{B_k\}} S(\rho_{\rm AB}|\{B_k\}). \tag{12}$$

For a pair of qubits, the concurrence introduced by Wootters,[8] the concurrence is defined as: $C(\rho_{\rm AB}) = \max[\lambda_1 - \lambda_2 - \lambda_3 - \lambda_4, 0]$, where the quantities $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$ are the square roots of the eigenvalues of the matrix product $R = \rho(\sigma_1^y \otimes \sigma_2^y)\rho^*(\sigma_1^y \otimes \sigma_2^y)$ in descending order. The ρ is the density operator of the pair and it can be either pure or mixed. The nonzero concurrence implies that the qubits 1 and 2 are entangled. Entanglement of formation is a monotonically increasing function of $C(\rho_{\rm AB})$. The concurrence $C(\rho_{\rm AB}) = 0$ corresponds to an unentangled state and $C(\rho_{\rm AB}) = 1$ corresponds to a maximally entangled state.

There exists an analytic expression about geometrical measure of quantum discord for any quantum state of a two-qubits system and more general quantum state of dimensional.[13,40] There exists a Bloch expression for any quantum state of two qubits system as follows:[41]

$$\rho^{\rm ab} = \frac{1}{4}\Big(I^{\rm a}\otimes I^{\rm b} + \sum_{i=1}^{3} x^i\sigma^i \otimes I^{\rm b} + \sum_{i=1}^{3} y^i I^{\rm a}\otimes\sigma^i + \sum_{i,j=1}^{3} t^{ij}\sigma^i\otimes\sigma^j\Big),$$

where $x^i = \mathrm{Tr}\rho(\sigma^i \otimes I^{\rm b})$, $y^i = \mathrm{Tr}\rho(I^{\rm a}\otimes\sigma^i)$, $t^{ij} = \mathrm{Tr}\rho(\sigma^i \otimes \sigma^j)$, $\boldsymbol{x} := (x_1, x_2, x_3)^{\rm t}$, and $\boldsymbol{y} := (y_1, y_2, y_3)^{\rm t}$ are the Bloch vectors of edge states $\rho^{\rm a}$ and $\rho^{\rm b}$, but $T := t_{ij}$ is the correlation matrix of two body quantum states. Then the geometric quantum discord of $\rho^{\rm ab}$ is

$$D_{\rm G}(\rho^{\rm ab}) = \frac{1}{4}(\| x \|^2 + \| T \|^2 - k_{\max}), \tag{13}$$

where $k_{\max}$ is the largest eigenvalue of the matrix $\boldsymbol{K} = \boldsymbol{x}\boldsymbol{x}^{\rm t} + \boldsymbol{T}\boldsymbol{T}^{\rm t}$.

3. Dynamical evolutions of various correlations of the model under the intrinsic decoherence

According to Milburn's equation[42] followed by the assumption that a system does not evolve continuously under unitary transformation for sufficiently short time steps, the master equation for pure phase decoherence is given by

$$\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -\mathrm{i}[H, \rho(t)] - \frac{1}{2\gamma}[H, [H, \rho(t)]], \tag{14}$$

where γ is the phase (intrinsic) decoherence rate, which is responsible for the decay of quantum coherence in the energy eigenstate basis, without the usual energy dissipation associated with the normal decay. The formal solution of the above master equation can be expressed as[42–47]

$$\rho(t) = \sum_{k=0}^{\infty} \frac{l^k}{k!} M^k(t)\rho(0)M^{\dagger k}(t), \tag{15}$$

where $\rho(0)$ is the density operator of the initial system and $M^k(t)$ is defined by

$$M^k(t) = H^k \exp(-\mathrm{i}Ht)\exp\left(-\frac{t}{2\gamma}H^2\right). \tag{16}$$

By inserting the completeness relation $\sum_n |\psi_n\rangle\langle\psi_n| = I$ of the energy eigenstate into the master equation,[43] the time evolution of the density operator for the system mentioned above can be given by

$$\rho(t) = \sum_{mn} \exp\left[-\frac{\gamma t}{2}(E_m - E_n)^2 - \mathrm{i}(E_m - E_n)t\right] \times \langle\psi_m|\rho(0)|\psi_n\rangle|\psi_m\rangle\langle\psi_n|, \tag{17}$$

where $E_{m,n}$ and $\psi_{m,n}$ are the eigenvalues and the corresponding eigenvectors, respectively. We assume that the system is initially prepared in the Bell state $|\Psi(0)\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$. From Eq. (16), the time evolution of $\rho(t)$ for this initial state of the system can be obtained as

$$\rho(t) = \begin{pmatrix} \alpha & \xi & \xi & \alpha \\ \beta & \omega & \omega & \beta \\ \beta & \omega & \omega & \beta \\ \alpha & \xi & \xi & \alpha \end{pmatrix}, \tag{18}$$

where

$$\alpha = \frac{E_{\rm J}^2(1 - \exp(-2t\gamma\mu)\cos[2t\sqrt{\mu}])}{4\mu};$$

$$\beta = \frac{E_{\rm J}[E_{\rm m} - \exp(-2t\gamma\mu)(E_{\rm m}\cos[2t\sqrt{\mu}] + \sqrt{\mu}\sin[2t\sqrt{\mu}]\mathrm{i})]}{4\mu};$$

$$\omega = \frac{2E_{\rm m}^2 + E_{\rm J}^2(1 + \exp(-2\mu t\gamma)\cos[2t\sqrt{\mu}])}{4\mu};$$

$$\xi = \frac{E_{\rm J}[E_{\rm m} - \exp(-2t\gamma\mu)(E_{\rm m}\cos[2t\sqrt{\mu}] - \sqrt{\mu}\sin[2t\sqrt{\mu}]\mathrm{i})]}{4\mu},$$

where $\mu = E_{\rm J}^2 + E_{\rm m}^2$.

Based on the definitions of C, CC, QD, and GQD, and Milburn's method for the description of the intrinsic decoherence, we will present a brief analysis on the correlation dynamics with the corresponding plots in the following.

From Fig. 1, it is easy to find that all the correlations finally reach their steady state values after some oscillations. That is, for the system parameters chosen as in the figure caption, the correlations may evolve into finite steady state values despite the intrinsic decoherence. The robustness of the correlations may be ranked in the order of C, QD, CC, and GQD.

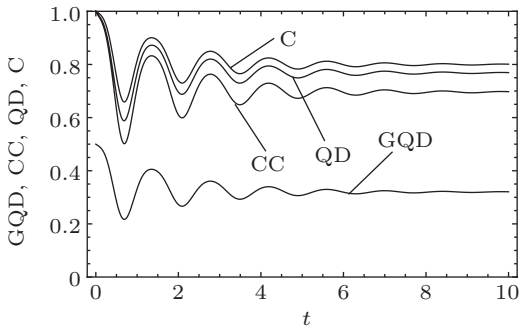


Fig. 1. Correlations versus t with $E_{\rm J}=1$, $E_{\rm m}=2$, and $\gamma=0.05$.

To examine the effects of system parameters $E_{\rm J}$ and $E_{\rm m}$ on the correlation dynamics under phase decoherence, we give the plots in Fig. 2(a) (Fig. 2(b)) for the correlations versus $E_{\rm J}$ ($E_{\rm m}$), with the other parameters fixed. Overall, the smaller $E_{\rm J}$ and the larger $E_{\rm m}$ may result in larger correlations. The rank of the steady state values of the correlations in Fig. 2(b) is the same as that in Fig. 1, while it is somewhat different in Fig. 2(a) in that QD is the highest instead of C. Again, the $E_{\rm m}$ may be used as an effective system parameter against the intrinsic decoherence in increasing the correlations.

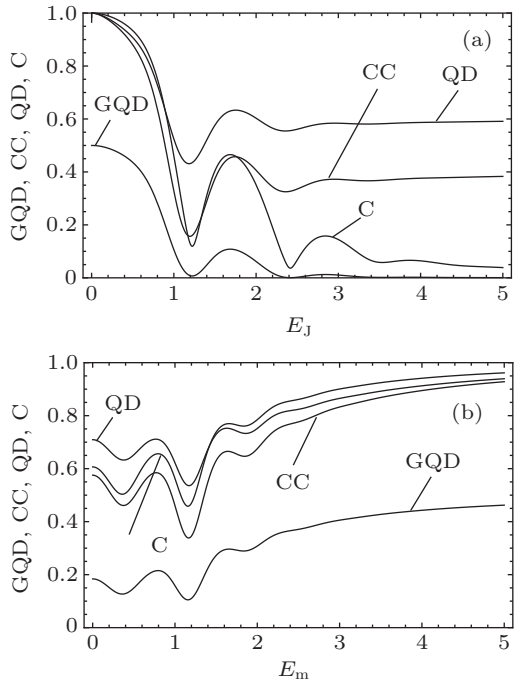


Fig. 2. (a) Correlations versus $E_{\rm J}$ with $E_{\rm m}=1$, $t=3$, and $\gamma=0.05$; (b) correlations versus $E_{\rm m}$ with $E_{\rm J}=1$, $t=5$, and $\gamma=0.05$.

4. Dense coding with the model under intrinsic decoherence

In the general dense coding, the sender performs one of the local unitary transformations $U_i \in U(d)$ on d-dimensional quantum system to put the initially shared entangled state ρ in $\rho_i = (U_i \otimes I_d)\rho(U_i^{\dagger} \otimes I_d)$ with *a priori* probability p_i ($i=0,1,\ldots,i_{\max}$), and then the sender sends off his quantum system to the receiver. Upon receiving this quantum system, the receiver performs a suitable measurement on ρ_i to extract the information. The optimal amount of information that can be conveyed is known to be bounded from above by Holevo quantity[48] $\chi = S(\overline{\rho}) - S(\rho)$, where $S(\rho) = -\mathrm{Tr}(\rho \log_2 \rho)$ denotes the von Neumann entropy and $\overline{\rho} = \sum_{i=0}^{i_{\max}} p_i \rho_i$ is the average density matrix of the signal ensemble. Since the Holevo quantity is asymptotically achievable,[49,50] one can use $\chi = S(\overline{\rho}) - S(\rho)$ as the definition of the capacity of dense coding.

At the next step, we discuss the dense coding by using the entangled states of the above model as a channel and give the intuitional description of the influence of the intrinsic decoherence on dense coding channel capacity in terms of a three-dimensional diagram. From Fig. 3, it can be seen that the dense coding channel capacity χ oscillates periodically with the time for the small phase decoherence rates. As the decoherence effect increases, although the oscillatory behavior of the χ suffers a significant suppression, it approaches a final steady state value, which allows a valid dense coding.

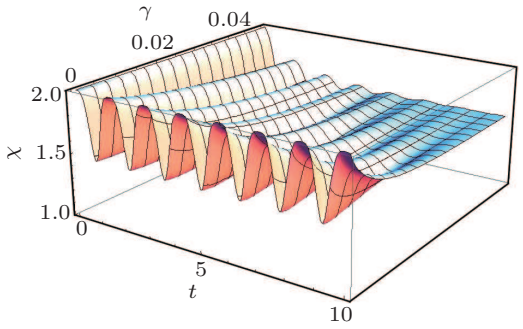


Fig. 3. (color online) Dense coding capacity χ versus t and γ with $E_{\rm J}=2$ and $E_{\rm m}=1$.

In order to examine the combinatory effects of $E_{\rm J}$, $E_{\rm m}$, and γ on the dense coding capacity, we give the plots χ versus $E_{\rm J}$ and γ, and χ versus $E_{\rm m}$ and γ in Figs. 4(a) and 4(b), respectively. The evolution time is long enough to guarantee χ to reach its final steady state value. It is found that the roles of the Josephson energy and mutual coupling energy in fighting against the intrinsic decoherence are opposite in that the smaller Josephson energy leads to the larger capacity, while the larger mutual coupling energy leads to the larger capacity. That is to say, the final steady state value of the dense coding

capacity is still high despite the phase decoherence, implying that the χ can still be kept highly immune to the decoherence via increasing the mutual coupling energy and/or decreasing the Josephson energy.

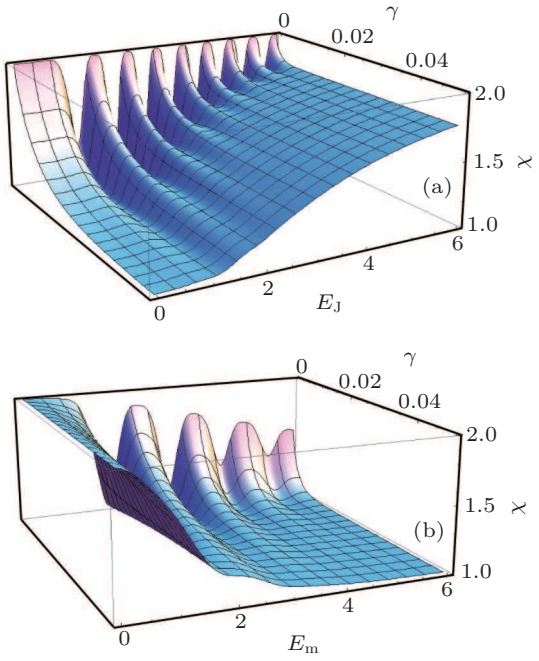


Fig. 4. (color online) (a) Dense coding capacity χ versus E_J and γ with $t = 5$ and $E_m = 0.7$; (b) dense coding capacity χ versus E_m and γ with $t = 6$ and $E_J = 2$.

5. Conclusion

In conclusion, we have examined the influence of intrinsic decoherence on various correlations in the model of two superconducting charge qubits coupled via a fixed capacitor. The results show that despite the phase decoherence all the correlations reach their steady state values after exhibiting some oscillations. The joint effects of the Josephson energy, mutual coupling energy between the charge qubits, and the intrinsic decoherence on the correlations and dense coding channel capacity are investigated. Importantly, for the model under consideration, it is possible to increase the correlations and the dense coding channel capacity via an appropriate combination of system parameters, in which the Josephson energy is smaller than the mutual coupling energy between the two charge qubits.

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