International Journal of Theoretical Physics, Vol. 45, No. 11, November 2006 (© 2006)
DOI: 10.1007/s10773-006-9170-8

Squeezing Effect of the Charge and Current in Mesoscopic Coupled Circuit with Alternating Source

Ju-ju Hu,[1,2,3] Shi-hua Cai,[1,2] and Ying-hua Ji[1,2]

Published Online: April 6, 2006

We study the dynamic evolution of a mesoscopic coupled circuit with alternating source and solve its time-dependent Schrödinger equation with the help of the time dependent invariant of the Hermitian operator. It indicates that the state of the system can evolve a generalized squeezed state. The results show that in certain circumstance, compared to the initial vacuum state, either the charges or the currents in two meshes are squeezed simultaneously in the same extent. The expression of the nonadiabatic geometric phase in the circuit is also obtained.

KEY WORDS: mesoscopic coupled circuits; alternating source; the dynamic evolution; squeezing effect.
PACS numbers: 73.23.-b; 73.63.-b; 73.21.-b.

1. INTRODUCTION

Nanoelectronics have been developing rapidly in recent years. Its main goal is a continued downscaling of integrated circuits and the consequent upscaling of functions of a chip. With the advancement of nanotechnology, it is possible to fabricate mesoscopic system of size within the phase coherence length so that electrons throughout the whole system retain the phase memory. This will have a tremendous impact on science, technology, and society as a whole. In such systems, the quantum effects of the devices must be taken into account. Besides the energy quantization and the interference of wave functions, the charge quantization also has significant effects in nanoelectronics. Louisell studied the quantization of an LC circuit with a source and found that the Hamiltonian of the circuit is similar to that of a driven harmonic oscillator (Allahverdyan and

[1] Department of Physics, Jiangxi Normal University, Nanchang, Jiangxi 330027, China.
[2] Key Laboratory of Optoelectronic & Telecommunication of Jiangxi, Nanchang, Jiangxi 330027, China.
[3] To whom correspondence should be addressed at Department of Physics, Jiangxi Normal University, Nanchang, Jiangxi 330027, China; e-mail: zouqh2002@sohu.com or hjj2006@jxnu.edu.cn

Nieuwenhuizen, 2002; Ji *et al.*, 2003; Li and Chen, 1996; Flores, 2002; Liang and Fan, 2001). The Refs. (Fan and Pan, 1998; Ji *et al.*, 2002; Li, 1998) discussed the quantum fluctuation at infinite temperature by thermodynamics theory, the Coulomb blockade of tunneling, and Bloch oscillations in mesoscopic circuit. Influence of coupling effects to quantum effect were studied in Refs. (Yu and Liu, 1998). In these researches, people mostly discussed either without external source or in adiabatic approximation, the external source being treated to direct source. In fact, the external alternating source must be taken into account in most time.

In this paper, we study dynamic of a mesoscopic coupled capacitor circuit with alternating source. We obtain closed formulas for the time evolution of quantum states and the evolution operator of the circuit by selecting proper Hermitian invariant operator. The research results indicate that the state of the mesoscopic LC circuit with ac source can evolve the generalized squeezed states.

2. QUANTUM HAMILTONIAN

The coupled capacitor circuit with voltage source is drawn in Fig. 1. The quantum Hamiltonian of this system is

$$H = \frac{1}{2L_1}p_1^2 + \frac{1}{2L_2}p_2^2 + \frac{1}{2}L_1\omega_1^2 q_1^2 + \frac{1}{2}L_2\omega_2^2 q_2^2 - \frac{1}{C_3}q_1 q_2 + q_1\varepsilon(t), \quad (1)$$

$$\omega_1^2 = \frac{C_1 + C_3}{L_1 C_1 C_3}, \quad \omega_2^2 = \frac{C_2 + C_3}{L_2 C_2 C_3},$$

$$\varepsilon(t) = \varepsilon \cos(\omega_{ex} t).$$

where L_1, L_2, C_1, C_2 stand for the inductance and capacity of the coupled mesh, respectively; C_3 stands for the capacity of the coupled branch; $\varepsilon(t)$ the external voltage source, a function of time. q_j is the electric charge, and $p_j = L_j \dot{q}_j$ the conjugate momenta. The quantum operators satisfy the commutation

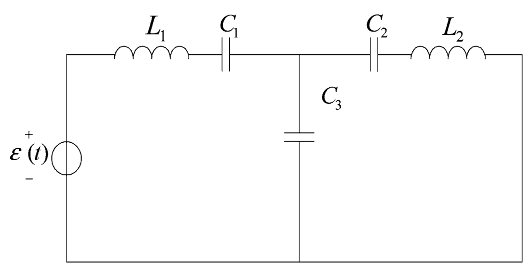

Fig. 1. Coupled circuit of capacitors with alternating source.

relation $[q_1, p_1] = i$, $[q_2, p_2] = i(\hbar = 1)$. Equation (1) represents a pair of quantized harmonic oscillators which are coupled each other. We find a unitary operator U that can make Hdiagonalization. The operator U is expressed in coordinate representation(Lei *et al.*, 2001)

$$U_1 = \iint_{-\infty}^{+\infty} dq_1 dq_2 \left| \begin{pmatrix} K\cos\theta & K\sin\theta \\ K^{-1}\sin\theta & K^{-1}\cos\theta \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \right\rangle \left\langle \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \right|, \tag{2}$$

where

$$K^2 = \sqrt{\frac{L_2}{L_1}}, \tag{3}$$

$$\tan(2\theta) = \frac{2C_1C_2\sqrt{L_1L_2}}{L_2C_2(C_1 + C_3) - L_1C_1(C_2 + C_3)}. \tag{4}$$

Then we can transform Eq. (1) into the separable form following

$$H = \frac{1}{2}\alpha_1 P_1^2 + \frac{1}{2}\alpha_2 P_2^2 + \frac{1}{2}\beta_1 Q_1^2 + \frac{1}{2}\beta_2 Q_2^2 + K(Q_1\cos\theta + Q_2\sin\theta)\varepsilon(t). \tag{5}$$

Because of the transformation U, a mesoscopic coupled circuit can be looked as a pair of quantum harmonic oscillators independent to each other, with their frequencies being

$$\Omega_1^2 = \alpha_1\beta_1, \quad \Omega_2^2 = \alpha_2\beta_2.$$

Where

$$\alpha_1 = L_1^{-1}K^{-2}\cos^2\theta + L_2^{-1}K^2\sin^2\theta - C_3^{-1}\sin(2\theta),$$
$$\alpha_2 = L_1^{-1}K^{-2}\sin^2\theta + L_2^{-1}K^2\cos^2\theta + C_3^{-1}\sin(2\theta),$$
$$\beta_1 = L_1K^2\omega_1^2\cos^2\theta + L_2K^{-2}\omega_2^2\sin^2\theta - C_3^{-1}\sin(2\theta),$$
$$\beta_2 = L_1K^2\omega_1^2\sin^2\theta + L_2K^{-2}\omega_2^2\cos^2\theta + C_3^{-1}\sin(2\theta).$$

We define the annihilation and creation operators a_j and a_j^+ by the relations

$$Q_j = \sqrt{\frac{\alpha_j}{2\Omega_j}}(a_j^+ + a_j), \quad P_j = i\sqrt{\frac{\Omega_j}{2\alpha_j}}(a_j^+ - a_j).$$

Then, the Hamiltonian of the circuit is

$$H(t) = \Omega_1 a_1^+ a_1 + \Omega_2 a_2^+ a + A(a_1^+ + a_1) + B(a_2^+ + a_2). \tag{6}$$

$$A = \varepsilon \cos\theta \sqrt{\frac{\alpha_1 L_2}{2L_1\Omega_1}} \cos\omega_{ex} t,$$

$$B = \varepsilon \sin\theta \sqrt{\frac{\alpha_2 L_2}{2L_1\Omega_2}} \cos\omega_{ex} t.$$

The $H(t)$ given by Eq. (6) depends on time. The time evolution of dynamical systems with an explicitly time dependent Hamiltonian has been interesting over the past several decades and has attracted considerable attention because of its various applications. An important aspect in this regard is the geometric phase associated with the evolution of the states in certain circumstance. In terms of physical applications, the geometric phase, which reveals the gauge structure associated with a phase shift in quantum mechanics, has attracted a lot of interest in a wide variety field (Berry, 1984; Galvez *et al*., 2003; Shao *et al*., 1999). Lewis and Riesenfeld (LR) started investigating the dynamics of time dependent systems long ago with a method of Hermitian invariants. It has been shown that the general solution of the time dependent Schrödinger equation can expressed as a linear superposition of eigenstates of the invariant operator (Hartley and Ray, 1982). In this paper, using quantum invariant theory of Lewis and Riesenfeld, we investigate evolution of quantum state of the mesoscopic coupled circuit.

3. INVARIANT HERMITIAN

According to the quantum invariant theory of Lewis and Riesenfeld, we can select appropriate Hermitian invariants $I(t)$ to satisfy the following formula

$$i\frac{\partial I(t)}{\partial t} + [I(t), H(t)] = 0, \tag{7}$$

with $I^+(t) = I(t)$. Then the general solution of the time dependent Schrödinger equation can be expressed as a linear superposition of eigenstates of the invariant operator, and the time evolution operator of the system can be obtained. For a given time dependent Hamiltonian $H(t)$, a invariant Hermitian operator $I(t)$is defined by the relation

$$I(t) = D[z_1(t)]D[z_2(t)]S[R(t)]K_0S^+[R(t)]D^+[z_2(t)]D^+[z_1(t)]. \tag{8}$$

$$K_0 = a_1^+a_1 + a_2^+a_2$$

$D[z(t)]$ is displacement operator which is defined

$$D[z_j(t)] = \exp[z_j(t)a_j^+ - z_j^*(t)a_j],$$

and $S[R(t)]$ squeezing operator

$$S[R(t)] = \exp\left(R^*a_1a_2 - Ra_1^+a_2^+\right).$$

$z(t)$ and $R(t)$ are complex time dependent function:

$$z_j(t) = \rho_j(t)\exp[i\delta_j(t)], \tag{9}$$

$$R(t) = r(t)\exp[i\varphi(t)]. \tag{10}$$

For the sake of simplify, $z(t)$, $R(t)$, $\rho(t)$, $\delta(t)$, $r(t)$, and $\varphi(t)$ are replaced by z, R, ρ, δ, r and φ, correspondingly, in the following discussion. Using the displacement and squeezing transformation,

$$D(z_j)a_jD^+(z_j) = a_j - z_j,$$
$$S(R)a_1S^+(R) = a_1\cosh r + a_2^+\sinh r\exp(i\varphi),$$
$$S(R)a_2S^+(R) = a_2\cosh r + a_1^+\sinh r\exp(i\varphi).$$

We obtain

$$I(t) = (a_1^+a_1 + a_2^+a_2)\cosh\,2r + \frac{1}{2}(a_1^+a_2^+e^{i\varphi} + a_1a_2e^{-i\varphi})\sinh\,2r,$$
$$-a_1^+f_1 - a_1f_1^* - a_2^+f_2 - a_2f_2^* + h. \tag{11}$$

where

$$f_1(t) = z_1(t)\cosh 2r + z_1^*(t)\sinh 2r\exp(i\varphi), \tag{12}$$

$$f_2(t) = z_2(t)\cosh 2r + z_2^*(t)\sinh 2r\exp(i\varphi), \tag{13}$$

$$h = (\rho_1^2 + \rho_2^2)\cosh 2r + [\rho_1\rho_2\sinh 2r\cos(\delta_1 + \delta_2 - \varphi)]. \tag{14}$$

Substituting Eqs. (4) and (9) into Eq. (5), after a long but direct calculation, we obtain the following auxiliary equations:

$$\dot{r} = 0, \tag{15}$$

$$\dot{\varphi} = -\Omega_1 - \Omega_2, \tag{16}$$

$$\dot{f_1} = i[-\Omega_1 f_1 - A\cosh 2r + B\sinh 2r\exp(i\varphi)], \tag{17}$$

$$\dot{f_2} = i[-\Omega_2 f_2 - B\cosh 2r + A\sinh 2r\exp(i\varphi)], \tag{18}$$

$$\dot{h} = iA(f_1 - f_1^*) + iB(f_2 - f_2^*). \tag{19}$$

Based on the given initial condition, Solving above auxiliary equations, we can obtain the relevant parameters, i.e., the quantum invariants $I(t)$.

Let $\{|n_1, n_2\rangle\}$denote the eigenstates of the number operatorK_0, which are the analogs of the number states of the harmonic oscillator, then we have

$$K_0\,|n_1, n_2\rangle = (n_1 + n_2)\,|n_1, n_2\rangle\,.$$

Then, the state

$$|z, r, n\rangle = D[z_1(t)]D[z_2(t)]S[R(t)]\,|n_1, n_2\rangle\,, \tag{20}$$

is just the normalized eigenstate of the invariant operator $I(t)$with the time independent eigenvalue spectrum, i.e.,

$$I(t)\,|z,r,n\rangle = (n_1+n_2)\,|z,r,n\rangle\,.$$

4. THE TIME EVOLUTION OF OPERATOR

Once the invariant operator and its eigenvalues are known, the solutions of the circuit can be easily found. Suppose that $|\Psi(t)\rangle$ is the state vector of the mesoscopic circuit that evolves according to the time dependent Schrödinger equation

$$i\hbar\frac{\partial\Psi(t)}{\partial t} = H(t)\Psi(t),$$

according to the quantum Invariant theory of Lewis and Riesenfeld (LR), the solution of this equation can be expressed

$$|\Psi(t)\rangle = \sum_{n_1,n_2} C_{n_1,n_2}\exp(i\alpha_{n_1,n_2})D(z_1)D(z_2)S(r)\,|n_1,n_2\rangle, \tag{21}$$

where the expansion coefficients C_n are independent of time and α_n is the LR phase. The eigenstates of the invariant operator evolve according to the time dependent Schrödinger equation as long as the LR phase satisfies

$$\alpha_n = \gamma_n + \beta_n.$$

Where the γ_n is defined the LR geometric phase by

$$\gamma_n = \int_0^t \left\langle z,r,n\left|i\frac{\partial}{\partial t}\right|z,r,n\right\rangle dt'. \tag{22}$$

And

$$\beta_n = -\int_0^t \langle z,r,n|H(t')\,|z,r,n\rangle\,dt', \tag{23}$$

is the usual dynamical phase. The LR phase α_n is well defined for general nonadiabatic and noncyclic evolution of the system. It represents a phase change during the time evolution of the state. Once the dynamical phase is removed, the phase difference accumulated during the time evolution has a purely geometric origin.

We now derive the time evolution operator of the circuit, which is useful to investigate the dynamic of the system. When $t=0$, from Eq. (21), we have

$$|\Psi(0)\rangle = D(z_{10})D(z_{20})S(r_0)\sum_{n_1,n_2} C_{n_1,n_2}\exp(i\alpha_{n_1,n_2})\,|n_1,n_2\rangle. \tag{24}$$

Therefore we obtain

$$\sum_{n_1,n_2} C_{n_1,n_2}\,|n_1,n_2\rangle = S^{+}(r_0)D^{+}(z_{20})D^{+}(z_{10})\,|\Psi(0)\rangle\,. \tag{25}$$

So the quantum state of time evolution of the system is

$$|\Psi(t)\rangle = \exp(\mathrm{i}\sigma)D(z_1)D(z_2)S(r)\exp[-\mathrm{i}(\varepsilon_1 a_1^+ a_1 + \varepsilon_2 a_2^+ a_2)]S^+ \times (r_0)D^+(z_{20})D^+(z_{10})\,|\psi(0)\rangle \quad (26)$$

where

$$2\sigma = \int_0^t \{i(\dot{z}_1 z_1^* + \dot{z}_2 z_2^* - z_1\dot{z}_1^* - z_2\dot{z}_2^*) - 2\Omega_1 z_1 z_1^* - 2\Omega_2 z_2 z_2^*\}\,dt' - 2\int_0^t [(\dot{\varphi} + \Omega_1 + \Omega_2)\sinh^2 r + A(z_1 + z_1^*) + B(z_2 + z_2^*)]\,dt'$$

$$\varepsilon_1 = \int_0^t [\dot{\varphi}\sinh^2 r + \Omega_1\cosh^2 r + \Omega_2\sinh^2 r - G\cos\varphi\sinh 2r]\,dt',$$

$$\varepsilon_2 = \int_0^t [\dot{\varphi}\sinh^2 r + \Omega_1\sinh^2 r + \Omega_2\cosh^2 r - G\cos\varphi\sinh 2r]\,dt'$$

The time evolution operator of the circuit is

$$U_2(t) = \exp\{i\sigma\}D(z_1)D(z_2)S(r)\exp[-i(\varepsilon_1 a_1^+ a_1 + \varepsilon_2 a_2^+ a_2)] \times S^+(r_0)D^+(z_{20})D^+(z_{10}). \quad (27)$$

The time evolution from an arbitrary initial state can be calculated in terms of the unitary operator. For the mesoscopic system evolving from an initial wave function $|\Psi(0)\rangle$ to a final wave function$|\Psi(t)\rangle$, since $|\Psi(t)\rangle$cannot be obtained from $|\Psi(0)\rangle$by a multiplication with a complex number, the initial and final states are distinct and the evolution is noncyclic.

5. SQUEEZING EFFECT

In Heisenberg picture, the time evolutions of any operator a_j are

$$a_1(t) = x_1(t)(a_1 - z_{10}) + x_2(t)(a_2^+ + z_{20}^*) + z_1, \quad (28)$$

$$a_2(t) = x_3(t)(a_2 - z_{20}) + x_4(t)(a_1^+ + z_{10}^*) + z_2. \quad (29)$$

where

$$x_1(t) = \cosh r_0\cosh r\exp(-i\varepsilon_1) - \sinh r_0\sinh r\exp[i(\varepsilon_2 + \varphi - \varphi_0)], \quad (30)$$

$$x_2(t) = \sinh r_0\cosh r\exp[-i(\varepsilon_1 - \varphi_0)] - \cosh r_0\sinh r\exp[i(\varepsilon_2 + \varphi)], \quad (31)$$

$$x_3(t) = \cosh r_0\cosh r\exp(-i\varepsilon_2) - \sinh r_0\sinh r\exp[i(\varepsilon_1 + \varphi - \varphi_0)], \quad (32)$$

$$x_4(t) = \sinh r_0\cosh r\exp[-i(\varepsilon_2 - \varphi_0)] - \cosh r_0\sinh r\exp[i(\varepsilon_1 + \varphi)]. \quad (33)$$

We assume that the circuit prepared initially in vacuum state$|\Psi(0)\rangle = |0, 0\rangle$. Then, in the state$|\Psi(t)\rangle$, we can obtain quantum fluctuations of the Q_j and P_j

$$\left\langle(\Delta Q)_1^2\right\rangle = \frac{\alpha_1}{2\Omega_1}(x_1^* x_1 + x_1^* x_2^* + x_1 x_2 + x_2^* x_2), \tag{34}$$

$$\left\langle(\Delta P)_1^2\right\rangle = \frac{\Omega_1}{2\alpha_1}(x_1^* x_1 - x_1^* x_2^* - x_1 x_2 + x_2^* x_2), \tag{35}$$

$$\left\langle(\Delta Q)_2^2\right\rangle = \frac{\alpha_2}{2\Omega_2}(x_3^* x_3 + x_3^* x_4^* + x_3 x_4 + x_4^* x_4), \tag{36}$$

$$\left\langle(\Delta P)_2^2\right\rangle = \frac{\Omega_2}{2\alpha_2}(x_3^* x_3 - x_3^* x_4^* - x_3 x_4 + x_4^* x_4). \tag{37}$$

With the inverse transformation of Eq. (2) and Eqs. (34)–(37), we can obtain the quantum fluctuation of the charges and currents in both meshs. Since we supposed the initial state to be vacuum state, the initial squeezing factor should be $r_0 = 0, \varphi_0 = 0$. It indicates that the system is not squeezed originally but squeezed with time evolution. What must be paid much attention is that the squeezing extent parameter is invariable during the evolution of the system with external source by Eq. (15).

When $r_0 = 0$ and $\varphi_0 = 0$, Eqs. (30)–(33) can be written as:

$$\begin{aligned} x_1(t) &= \cosh r \exp(-i\varepsilon_1), \\ x_2(t) &= -\sinh r \exp[i(\varepsilon_2 + \varphi)], \\ x_3(t) &= \cosh r \exp(-i\varepsilon_2), \\ x_4(t) &= -\sinh r \exp[i(\varepsilon_1 + \varphi)]. \end{aligned}$$

So the quantum fluctuations of the charges and currents can be obtained by Eq. (16).

$$\begin{aligned} \left\langle(\Delta q)_1^2\right\rangle = \sqrt{\frac{L_2}{L_1}} \Bigg\{ &\cosh 2r \left(\frac{\alpha_1 \cos^2\theta}{2\Omega_1} + \frac{\alpha_2 \sin^2\theta}{2\Omega_2}\right) \\ &- \sinh 2r \left(\frac{\alpha_1 \cos^2\theta}{2\Omega_1} + \frac{\alpha_2 \sin^2\theta}{2\Omega_2}\right) [\cos(2\Omega_1 t) + \cos(2\Omega_2 t)] \Bigg\}, \end{aligned} \tag{38}$$

$$\begin{aligned} \left\langle(\Delta p)_1^2\right\rangle = \sqrt{\frac{L_1}{L_2}} \Bigg\{ &\cosh 2r \left(\frac{\Omega_1 \cos^2\theta}{2\alpha_1} + \frac{\Omega_2 \sin^2\theta}{2\alpha_2}\right) \\ &+ \sinh 2r \left(\frac{\Omega_1 \cos^2\theta}{2\alpha_1} + \frac{\Omega_2 \sin^2\theta}{2\alpha_2}\right) [\cos(2\Omega_1 t) + \cos(2\Omega_2 t)] \Bigg\}, \end{aligned} \tag{39}$$

$$\left\langle (\Delta q)_2^2 \right\rangle = \sqrt{\frac{L_1}{L_2}} \left\{ \cosh 2r \left(\frac{\alpha_1 \sin^2\theta}{2\Omega_1} + \frac{\alpha_2 \cos^2\theta}{2\Omega_2} \right) \right.$$
$$\left. - \sinh 2r \left(\frac{\alpha_1 \sin^2\theta}{2\Omega_1} + \frac{\alpha_2 \cos^2\theta}{2\Omega_2} \right) [\cos(2\Omega_1 t) + \cos(2\Omega_2 t)] \right\}, \quad (40)$$

$$\left\langle (\Delta p)_2^2 \right\rangle = \sqrt{\frac{L_2}{L_1}} \left\{ \cosh 2r \left(\frac{\Omega_1 \sin^2\theta}{2\alpha_1} + \frac{\Omega_2 \cos^2\theta}{2\alpha_2} \right) \right.$$
$$\left. + \sinh 2r \left(\frac{\Omega_1 \sin^2\theta}{2\alpha_1} + \frac{\Omega_2 \cos^2\theta}{2\alpha_2} \right) [\cos(2\Omega_1 t) + \cos(2\Omega_2 t)] \right\}. \quad (41)$$

Clearly, when $(\Omega_1 + \Omega_2)t = k\pi$,

$$\left\langle (\Delta q)_j^2 \right\rangle = \left\langle (\Delta q)_j^2 \right\rangle_0 e^{-r}, \quad \left\langle (\Delta p)_j^2 \right\rangle = \left\langle (\Delta p)_j^2 \right\rangle_0 e^{r}. \quad (42)$$

The suffix "0" represents the corresponding quantum fluctuations of the original vacuum state. Formula (42) indicates that correspond to the original vacuum state, charges are squeezed, but currents are not.

When $(\Omega_1 + \Omega_2)t = k\pi + \frac{\pi}{4}$,

$$\left\langle (\Delta q)_j^2 \right\rangle = \left\langle (\Delta q)_j^2 \right\rangle_0 e^{r}, \quad \left\langle (\Delta p)_j^2 \right\rangle = \left\langle (\Delta p)_j^2 \right\rangle_0 e^{-r}, \quad (43)$$

currents are squeezed, but charges are not.

6. CONCLUSION

We have studied the dynamic evolution of the mesoscopic coupled circuits with external ac source by using the invariant operator method. We show that the quantum state of the system can evolve a generalized squeezed and have obtained the quantum fluctuations of the circuits. The results show that in certain circumstance, compared to the vacuum state, either the charges or the currents in two meshes are squeezed simultaneously in the same extent. We can discuss the factors arousing squeezing. From Eq. (15), $\dot{r} = 0$, which shows that the interaction of the system with the external source will not arouse squeezing effects; it is the certain result of without considering the coupling energy aroused by the interference superposition of the wavefunction of the electrons in the both electrodes of mesoscopic capacitor. But from Eq. (2), we can see that the operator U_1causes not only rotation transformation but also squeezing transformation. For example, as the factor K^2 appears in charges, its inverse K^{-2} appears in currents. It indicates that squeezing is aroused by the coupled factor of the system.

ACKNOWLEDGMENTS

This work is supported by Foundation of Science and Technology of Education Office of Jiangxi Province, China under the Grant No. [2005]92. and by Foundation of Key Laboratory of Optoelectronic & Telecommunication of Jiangxi province, China under the Grant No. 2004006.

REFERENCES

Allahverdyan, A. E. and Nieuwenhuizen, Th. M. (2002). Testing the violation of the clausius inequality in nanoscale electric circuits. *Physical Review B* **66**, 115309.

Berry, M. V. (1984), Quantal phase factors accompanying adiabatic changes. *Proceedings of Royal Society of London* **392**, 45

Fan, H. Y. and Pan, X. Y. (1998). Quantization and squeezed state of two L-C circuit with mutual-inductance. *Chinese Physics Letters* **15**(9), 625.

Flores, J. C. (2002). Mesoscopic circuits with charge discreteness: Quantum current magnification for mutual inductances. *Physical Review B* **66**, 153410.

Galvez, E. J., Crawford, P. R., and Sztul, H. I., *et al.* (2003). Geometric phase associated with mode transformations of optical beams bearing orbital angular momentum. *Physical Review Letters* **90**, 203901.

Hartley, J. G. and Ray, J. R. (1982). Solutions to the time-dependent Schrödinger equation, *Physical Review A* **25**, 2388.

Ji, Y. H., Luo, H. M., and Wu. Y. Y. (2003). Behaviors of mesoscopic LC circuit in the external magnetic field. *Physics Letters A* **318**, 141.

Ji, Y. H., Rao, J. P., and Lei, M. S. (2002). Quantum tunneling effect in the mesoscopic LC circuit. *Acta Physica Sinica* **51**(2), 395 (in Chinese).

Lei, M. S., Ji, Y. H., and Xie, F. S. (2001). Quantum squeezing effects of a non-dissipative mesoscopic circuit with coupled inductor and capacitors. *Chinese Physics Letters* **18**(2), 163.

Li, Y. Q. (1998). Mesoscopic quantum circuit theory to persistent current and Coulomb blockade, In P. Kasperkovitz and D. Grau, eds. *Proceedings of the* 5^{th} *Wigner Symposium*, *World Scientific, Singpore*, pp. 307–310.

Li, Y. Q. and Chen, B. (1996). Quantum theory for mesoscopic electric circuit. *Physical Review B* **53**(7), 4027.

Liang, X. T. and Fan, H. Y. (2001). Quantum fluctuations in mesoscopic resistance-inductance capacitance electric circuits at finite temperature. *Chinese Physics* **10**, 486.

Shao, B., Zou, J., and Li, Q. S. (1999). Geometric phase in a mesoscopic Josephson junction with classical driving source. *Physical Review B* **60**, 9714.

Yu, G. A., Yu, Z. X., and Liu, Y. H. (1998). Quantum mechanical effects in a non-dissipation mesoscopic coupled circuit in the presence of source. *Communication in Theoretical Physics* **30**(2), 297.