Polar pumped current in quantum nano rings

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Abstract
By applying electric harmonic signals on two point of a quantum ring with phase difference Φ, the induced current is calculated theoretically. The method is based on defining all the operators in the Hilbert space of side band states defined in terms of Floquet theorem. Using this method, we have calculated the electronic pumped current as a function of phase difference of applied electric signals. By controlling on phase difference, it is shown that a polar pumped current can be induced in quantum ring.

Key words
Pumped current, Quantum nano rings, Electric harmonic signals.

1. Introduction

Quantum rings, which are artificial nanoscale clusters that confine electrons in three dimensions, have attracted increasing attention due to their unique physical properties.

Recent successful fabrication of self-assembled quantum rings (QR's) in nanometer dimensions [Garcia, 1997; Lorke, 2000; Mailly, 1993; Mano, 2005] has triggered a great deal of interest in theoretical and experimental researches. In such tiny systems, the wavelength of electrons is comparable to the system size, and thus quantum effects become significant.

Quantum rings, which are artificial nanoscale clusters that confine electrons in three dimensions, have attracted increasing attention due to their unique physical properties, such as high oscillator strength for the ground-state band-to-band transition [Pettersson, 2000], magnetic flux trapping of conducting or superconducting rings [Bagci and Matveev, 2002], possible tunable electronic states, stable vortex states of magnetic rings [Li, 2001; Yoo, 2003], large negative excitonic permanent dipole moment [Warburton, 2000], optical emission from a charged single quantum ring [Warburton, 2000],'bamboo' states of high-aspect- ratio magnetic rings [Wang, 2005] and tunable optical resonance of metal rings [Aizpurua, 2003]. The subject of parametric electron pump has attracted considerable attention in recent years [Wei and Shutenko, 2000]. An electron pump is a device which drives an electronic current by cyclic deformation of two or more system parameters [Aleiner and Brouwer, 1998]. This interesting device operates at zero bias potential. The idea of producing current by cyclic deformation of the system parameters was originally purposed by Thouless [Thouless, 1983].

Quite recently, this phenomena was observed experimentally by Switkes et al [Switkes, 1999]. for an open quantum dot where the pumping signal was adiabatically produced by cyclic variation of the confining potential. They, also, observed that in the weak pumping regime the pumped current is sinusoidal in the phase difference of deforming potential and non-sinusoidal in the strong pumping regime.

The original parametric pumping theory was formulated for the adiabatic regime, which is valid up to first order in the pumping frequency. Based on the adiabatic theory, the total charge pumped per cycle is proportional to the area enclosed by the path in the parameter space, and nonzero current requires at least two parameters. This condition is met for the input potentials having nonzero phase difference. But, this theory is not consistent with the observed experimental results for zero phase difference. The general expression for the averaged pumped current based on the time dependent S-matrix method for the adiabatic regime was derived by Brouwer [Brouwer, 1998]. It is important to note that the adiabatic condition dose not imply that the pumping amplitude should be small, in fact, the adiabatic condition requires that the oscillation period of the system parameters to be much larger than the Wigner delay time, the time that characterizes the duration of the interaction. In an attempt to go beyond the adiabatic approximation C. S.Tang and C. S. Chu considered a nonadiabatic quantum pumping phenomenon in a ballistic narrow constriction. They also studied the pumping effects of a pair of finite finger-gate array on a narrow channel. In another attempt to go beyond the adiabatic approximation, S.L. Zhu and et al based on the Floquet theorem, have developed a method for calculating the current in quantum pumps valid for all regimes. They calculated the pumped current through a mesoscopic region in the presence of a time-periodic potential. Interestingly, their method show nonzero pumping current at zero phase difference for asymmetric pumping amplitudes, consistent with the observed experimental values. [Switkes, 1999]

In this work, by invariant embedding method, we formulate the theory of pumped current for one dimensional quantum ring in tight binding approximation. By using Floquet theorem and the recursive method, the charge pumped current is calculated numerically versus the phase difference of the harmonic signals. Specially, it is shown that the magnitude and the polarity of the pumped current in the quantum ring depend on the phase difference.

2. The system in tight binding model

We consider a system of spinless electrons on a quantum ring with N sites. The time dependent Schrödinger equation of the system in the tight binding approximation by applying signals on the sites -1 and +1 is;

$$[E_{Fl}+\hat{H}_0(\omega)]|\psi_n(n)\rangle = -t_{n,n+1}|\psi(n)\rangle - t_{n,n-1}|\psi(n-1)\rangle + \hat{V}(n)|\psi(n)\rangle \quad (1)$$

where n labels the sites of the quantum ring and $t_{n,n+1}$ is the hopping parameter between sites n and n+1 and m labels the side-band states $\{|m\rangle\}, m=0,\pm1,\pm2,...$ and $\hat{V}(n)$ is the potential operator, given by;

$$\hat{V}(n)=\sum_{l=r'}^{r}\delta_{l,n}[V_l+\tilde{V}_l(e^{i\phi_l}\hat{T}_-+e^{-i\phi_l}\hat{T}_+)] \quad (2)$$

Equation (1) has the formal form of the tight binding Schrödinger equation with $\hat{H}_0(\omega)$, and $\hat{V}(n)$ being operators acting on the Hilbert space of the side-band states.

By defining Ricatti operator $\hat{\xi}(n)=\frac{\hat{\psi}(n+1)}{\hat{\psi}(n)}$ where $\hat{\psi}(n)$ is the solution of Schrödinger equation. We obtain left and right transmission operators and finally the average pumped current is evaluated by;

$$I(\mu)=\frac{e}{\pi\hbar}\int_{-2t_0}^{2t_0} dE f(E-\mu)\sum_m \frac{\sin(k_m)}{\sin(k_0)}|^2[|T^r_{m,0}(E)|^2-|T^l_{m,0}(E)|^2] \quad (3)$$

where f(E) is the Fermi-Dirac distribution function at zero temperature and it is supposed that the incoming wave is in the side-band state m=0 with energy E.

3. Results and Conclusion

We apply the method developed in the previous section to calculate the pumped current at zero temperature as a function of the phase difference. For all the calculations the dimension of the side-band space are taken to be equal to 41.

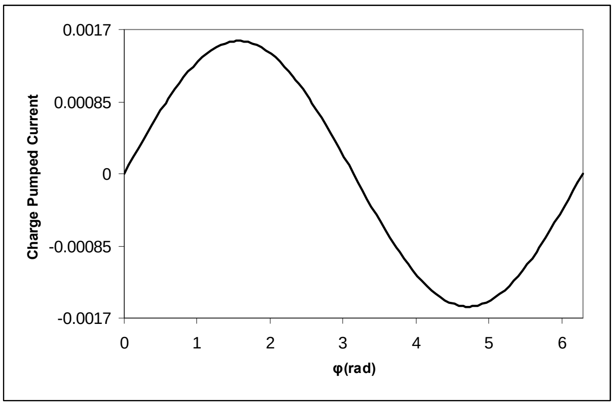

Figure.1. The charge pumped current in unit of $et_0/\pi\hbar$ for frequencies $\omega=0.3$ and $V_+=V_-=0.1$ (weak regime) as a function of the phase difference ϕ, for harmonic input electric signals. The energy scale is t_0, $E_f=0.0$.

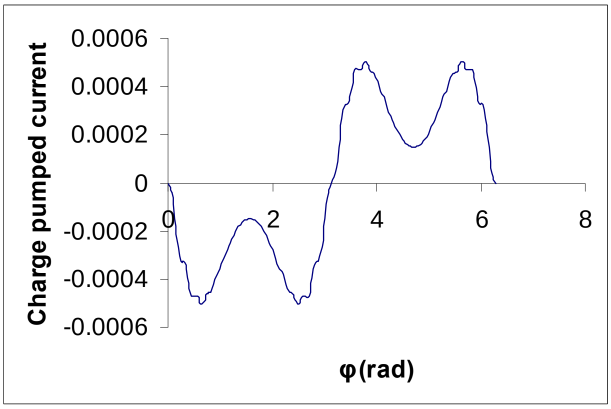

Figure.2. The charge pumped current in unit of $et_0 / \pi\hbar$ for frequencies $\omega = 0.3$ and $V_+ = V_- = 0.6$ (strong regime) as a function of the phase difference ϕ, for harmonic input electric signals. The energy scale is t_0, $E_f = 0.0$.

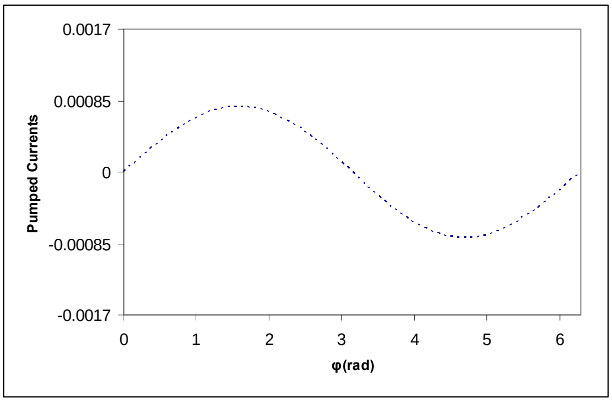

Figure.3. The charge pumped current in unit of $et_0 / \pi\hbar$ for frequencies $\omega = 0.4$ and $V_+ = V_- = 0.1$ (weak regime) as a function of the phase difference ϕ, for harmonic input electeric signals. The energy scale is t_0, $E_f = 0.0$

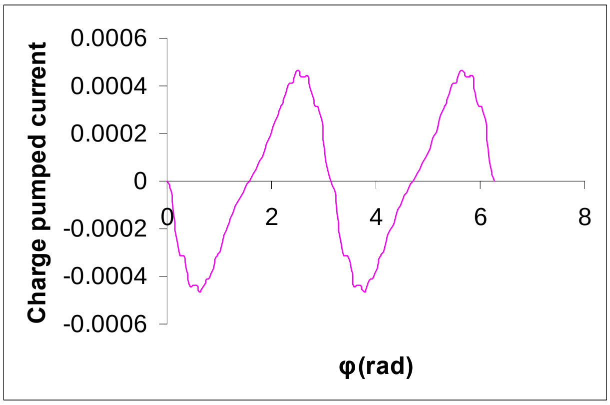

Figure.4. The charge pumped current in unit of $et_0 / \pi\hbar$ for frequencies $\omega = 0.4$ and $V_+ = V_- = 0.6$ (strong regime) as a function of the phase difference ϕ, for harmonic input electric signals. The energy scale is t_0, $E_f = 0.0$

This gives an accuracy of better than 10^{-8} for the calculated pumped currents. Also we consider chemical potential, μ, equal to zero and the hopping parameters, $t_{n,n+1} = t_0$, equal to one, as shown in figure 1, 2, 3 and 4 the pumped current is calculated as a function of the phase difference ϕ, for harmonic input signals in units of $et_0 / \pi\hbar$ for frequency $\omega = 0.3$. We show that by controlling the phase difference it is possible to change the direction of current and so the magnetic polarity of the quantum ring. It is important to notice for the phase difference equal to zero or π, the pumped current is zero. This can be realized the pumped current in adiabatic theory depends on the enclosed area in parameter space. In this symmetric case, the enclosed area in the parameter space is zero and as a result a vanishing pumped current.

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