Controlling the conductance and noise of driven carbon-based Fabry–Pérot devices

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We report on ac transport through carbon nanotube Fabry–Pérot devices. We show that tuning the intensity of the ac gating induces an alternation of suppression and partial revival of the conductance interference pattern. For frequencies matching integer multiples of the level spacing of the system Δ, the conductance remains irresponsive to the external field. In contrast, the noise in the low bias voltage limit behaves as in the static case only when the frequency matches an even multiple of the level spacing, thereby highlighting its phase sensitivity in a manifestation of the wagon-wheel effect in the quantum domain. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3147865]

Achieving control of the electrical response of nanometer scale devices by means of external fields is a main goal of nanoelectronics. This quest for control is usually pursued using static electric or magnetic fields, whereas the use of time-dependent excitations[1,2] remains much less explored. Besides offering captivating phenomena,[3–6] such as the generation of a dc current at zero bias voltage,[3,6,7] understanding the influence of ac fields becomes necessary if nanoscale devices are going to be integrated in everyday electronics.

Carbon based materials including fullerenes, graphitic systems, and polymers, are promising building blocks for these devices. Among them, carbon nanotubes[8] stand out due to their extraordinary mechanical and electrical properties.[8] Applications include transistors, sensors, and interconnects.[9] As compared to other molecular systems, single walled carbon nanotubes offer the unique opportunity of achieving almost ballistic transport. Indeed, thanks to the low resistance of the nanotube-electrodes contacts, Fabry–Pérot (FP) conductance oscillations were experimentally observed[10] and the current noise measured.[11] Although some experimental[12] and theoretical[13–17] studies on the effects of ac fields on nanotubes are available, the effect of ac fields on the conductance and noise in this FP regime is unknown: Is it possible to tune the interference pattern through ac fields? Can ac fields help us to unveil phase sensitive information encoded in the current noise?

In this letter, we answer the above questions by modeling the electronic transport through driven carbon nanotube FP resonators. We show that by tuning the frequency and intensity of a harmonic gate (see scheme in Fig. 1) one can control not only the conductance but also the current noise.[18] Moreover, we show that the current noise carries phase sensitive information not available in the static case.

Several approaches can be used to describe time-dependent transport. They include: The Keldysh formalism,[19–21] schemes that use density functional theory,[22] the equation of motion method,[23] and schemes that exploit the time-periodicity of the Hamiltonian through Floquet theory.[24,25] Here, as a general framework we use the Floquet scheme[25] combined with the use of Floquet–Green functions.[26] Within this formalism, the dc component of the time-dependent current as well as the dc conductance (called simply conductance hereafter), can be fully written in terms of the Green functions for the system.[2,26] The current noise can be obtained from the correlation function $S(t,t')=\langle[\Delta I(t)\Delta I(t')+\Delta I(t')\Delta I(t)]\rangle$, $\Delta I(t)=I(t)-\langle I(t)\rangle$ being the current fluctuation operator. The noise strength can be characterized by the zero frequency component of this correlation

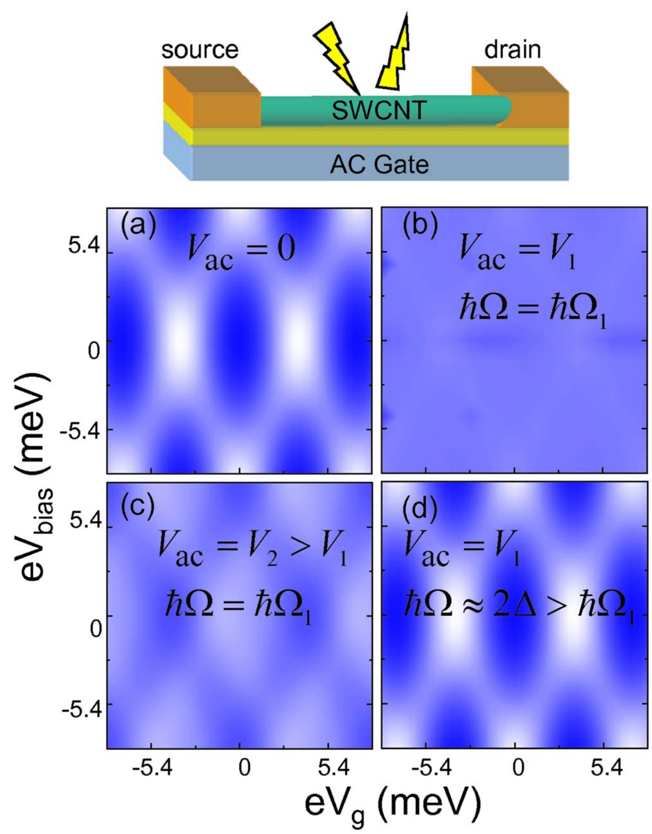

FIG. 1. (Color online) Top, scheme of the device considered in the text, a CNT connected to two electrodes and an ac gate. The panels marked with (a), (b), (c) and (d) are the FP conductance interference patterns (as a function of bias and gate voltages). The pattern observed with no ac gating [panel (a)] is modified when different driving frequencies and amplitudes are applied: (b) suppression, (c) revival and phase inversion, and (d) robustness. White and dark blue correspond to maximum and minimum conductances, respectively.

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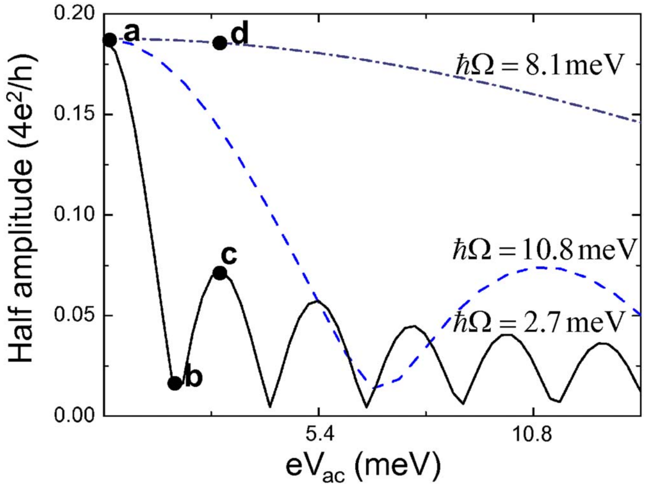

FIG. 2. (Color online) Half amplitude of the FP conductance oscillations as a function of the ac field intensity. These results are for a (24,0) metallic zig-zag nanotube of length $L=440$ nm and $\gamma_t=0.7\gamma_0$, at zero bias voltage and temperature.

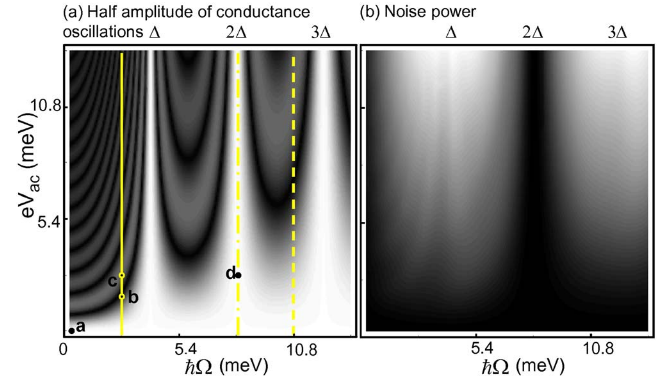

FIG. 3. (Color online) (a) Contour plot showing the half amplitude of the FP oscillations as a function of V_{ac} and Ω at zero temperature and bias voltage. (b) Same contour plot for the current noise $\bar{S}$. White in both figures is for maximum values of the half amplitude and noise, respectively.

function averaged over a driving period, $\bar{S}$, which can be casted in a convenient way within this formalism.[2] Further simplifications can be achieved by using the broadband approximation and an homogenous gating of the tube.[2]

For simplicity, we consider an infinite CNT described through a π-orbitals Hamiltonian[8] $H_e=\Sigma_i E_i c_i^+ c_i - \Sigma_{\langle i,j\rangle}[\gamma_{i,j} c_i^+ c_j + \text{H.c.}]$, where c_i^+ and c_i are the creation and annihilation operators for electrons at site i, E_i are the site energies and $\gamma_{i,j}$ are nearest neighbors carbon-carbon hoppings. To model the FP interferometer, a central part of length L (the "sample") is connected to the rest of the tube through matrix elements γ_t smaller than the hoppings in the rest of the tube which are taken to be equal to $\gamma_0=2.7$ eV.[8] L can be used to tune the level spacing $\Delta \propto 1/L$. Uniform gating of the sample is modeled as an additional on site energy $E_{j\in \text{CNT}}=eV_g+eV_{ac}\cos(\Omega t)$. This noninteracting model is justified when screening by a metallic substrate or by the surrounding gate lessens electron-electron interactions. When these interactions come into play effects beyond our present scope may emerge.[16]

In the following we consider a uniform gating of the tube, the same effects are expected for an ac bias or illumination with radiation of wavelength larger than the device length as in Ref. 27 where frequencies of up to 3 THz were achieved. At low to moderate frequencies ($\hbar\Omega<\Delta$), our main observation is that the amplitude of the FP conductance oscillations is reduced and can even be suppressed by tuning the intensity of the field. This is clearly shown in Fig. 2 (solid line) where the half amplitude of the conductance oscillations (computed at zero temperature) is shown as a function of the ac field intensity V_{ac}. Different curves correspond to different frequencies. Interestingly, for certain frequencies, the FP pattern is completely suppressed by tuning the intensity of the ac field, an effect which survives in the adiabatic limit.

Figure 1 shows the FP patterns obtained at the points marked on the curves in Fig. 2. There, by comparison with the static case (a), one can observe the suppression (b) and subsequent revival with a phase inversion (c) of the FP oscillations as V_{ac} increases. On the other hand, panel d shows a situation in which the frequency is tuned to meet the wagon-wheel or stroboscopic condition ($\hbar\Omega \approx n\Delta$, n integer). The overall dependence of the FP amplitude on both $\hbar\Omega$ and V_{ac} is better captured by the contour plot in Fig. 3(a). White corresponds to maximum values of the half amplitude and black to zero values. In general, although the field produces no appreciable change in the conductance whenever $\hbar\Omega \approx n\Delta$, a static behavior in the noise requires a more stringent condition as we will see later.

To rationalize these features let us first consider the adiabatic limit. In this limit, the period of the ac oscillation is long enough such that at each instant of time the system can be considered as static with an applied field which coincides with its instantaneous value. Within this approximation, the conductance is given by $G_{ad}=G_{avg}+A \times J_0(2\pi eV_{ac}/\Delta)\times\cos(2\pi eV_g/\Delta)$, where A and G_{avg} are the half amplitude and average value of the conductance in the static situation (vanishing ac field). We can see that the amplitude is modulated by a factor $J_0(2\pi eV_{ac}/\Delta)$. Thus, the FP interference is destroyed whenever $2\pi eV_{ac}/\Delta$ is a root of J_0. This relation would allow the experimental determination of the effective amplitude of the ac gating.

Deviations from the adiabatic result are due when the condition $\hbar\Omega \ll \Delta$ is not fulfilled. In this case, by assuming the broadband approximation, the dc conductance can be written in the Tien–Gordon[28] form $G(\varepsilon_F,V_g)=\Sigma_n|a_n|^2 G_{\text{static}}(\varepsilon_F+n\hbar\Omega,V_g)$, where $a_n=J_n(eV_{ac}/\hbar\Omega)$ represents the probability amplitude of emitting (absorbing) n photons. Thus, the averaging of the conductance takes place only among energies differing in discrete steps thereby rendering the smoothing of the oscillations less effective. A higher intensity of the field is therefore needed to suppress the conductance oscillations. Indeed, whenever $\hbar\Omega$ is commensurate with Δ the contrast of the FP pattern is insensitive to the ac field intensity. The dash-dotted line in Fig. 2 shows the amplitude vs. V_{ac} for a frequency close to such a condition.

Length dependence: In the infinite tube limit ($\Delta\to 0$) the FP oscillations disappear and, as long as higher subbands do not contribute to transport, the conductance becomes insensitive to the ac field.[14] For Fermi energies away from the charge neutrality point, our results remain valid provided that the energy range effectively probed by the field ($\sim\max(eV_{ac},N\hbar\Omega)$, where N is the typical number of photons) is small enough ($\max(eV_{ac},N\hbar\Omega)\ll\varepsilon_F$), thereby giving generality to our results for systems other than nanotubes.

The reservoirs are assumed to be in thermal equilibrium and current-induced heating is assumed not to compromise the tube stability. The typical current-induced heat flow is of about 50 nW, much below the experimental limits reported in Ref. 29.

The current noise as characterized by the dimensionless Fano factor (not shown here) is affected by the ac field only at high frequencies and driving amplitudes ($\hbar\Omega, V_{ac} \sim \Delta$). More interesting is the low bias, low temperature limit. For a static Hamiltonian, the noise power $\bar{S}$ vanishes in this limit as no fluctuations remain in the electron distributions. This is in striking contrast with the situation in which an ac field is applied to the conductor where there is always a nonzero current noise. In fact, even at zero temperature and bias, the ac field introduces probabilistic scattering processes (photon-assisted transitions), which add uncertainty to the effective electron distributions, thereby giving a nonvanishing contribution to the current noise.[2] In Fig. 3(b), a contour plot of the current noise $\bar{S}$ as a function of the driving frequency and ac intensity is presented. The color scale ranges from 6×10^{-27} A^2/Hz (black) to 2×10^{-25} A^2/Hz (white). The thermal contribution to the noise at 800 mK is estimated to be 6×10^{-27} A^2/Hz and would therefore not be noticeable in this color scale.

Figure 3(b) shows that, in contrast to what is observed for the conductance, whenever the wagon-wheel or stroboscopic condition is attained $\bar{S}$ does not behave as in the static case (i. e. different from zero). Indeed, there is a suppression of $\bar{S}$ only for $\hbar\Omega$ commensurate with even multiples of Δ. This is due to the fact that the noise under ac conditions is sensitive to the phase of the transmission amplitude which changes only by π (and not 2π) from one resonance to the next one. In between these minima there are local maxima whose intensity is proportional to V_{ac}. A similar situation was reported for a double quantum dot,[30] and for a driven system composed of two barriers of varying strength and a uniform varying potential in between.[31] The noise suppression observed here can be understood by using a simplified expression for the noise as done before for the conductance. The main conclusion is that when $\hbar\Omega = 2n\Delta$ (n integer), the noise behaves as in the static case. This effect can be visualized as a *manifestation of the wagon-wheel effect in the quantum domain* where a static behavior in the phase sensitive noise requires a doubling of the stroboscopic frequency.

In summary, we have analyzed the effects of ac gating on the conductance and noise of FP nanotube-based resonators. It was shown that the ac field can be used to tune the conductance and noise of the device. Suppression of the FP conductance oscillations can be achieved even in the adiabatic limit by tuning the driving amplitude. In contrast, when the driving frequency matches (a multiple of) the level spacing (wagon-wheel condition), the conductance coincides with the one of the static system. In contrast, the noise coincides with the static one only when $\hbar\Omega$ is commensurate with twice Δ (quantum wagon-wheel condition), therefore highlighting its phase sensitivity. Although here we considered only nanotubes, our main results are expected to be valid for more general FP nanoelectronic resonators.

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[1] G. Platero and R. Aguado, Phys. Rep. **395**, 1 (2004).
[2] S. Kohler, J. Lehmann, and P. Hänggi, Phys. Rep. **406**, 379 (2005).
[3] D. J. Thouless, Phys. Rev. B **27**, 6083 (1983).
[4] F. Grossmann, T. Dittrich, P. Jung, and P. Hänggi, Phys. Rev. Lett. **67**, 516 (1991).
[5] M. Wagner, Phys. Rev. A **51**, 798 (1995).
[6] B. L. Altshuler and L. I. Glazman, Science **283**, 1864 (1999); M. Switkes, C. M. Marcus, K. Campman, and A. C. Gossard, *ibid.* **283**, 1905 (1999).
[7] B. Kaestner, V. Kashcheyevs, S. Amakawa, M. D. Blumenthal, L. Li, T. J. B. Janssen, G. Hein, K. Pierz, T. Weimann, U. Siegner, and H. W. Schumacher, Phys. Rev. B **77**, 153301 (2008); A. Fujiwara, K. Nishiguchi, and Y. Ono, Appl. Phys. Lett. **92**, 042102 (2008); B. Kaestner, C. Leicht, V. Kashcheyevs, K. Pierz, U. Siegner, and H. W. Schumacher, *ibid.* **94**, 012106 (2009).
[8] J.-C. Charlier, X. Blase, and S. Roche, Rev. Mod. Phys. **79**, 677 (2007); R. Saito, G. Dresselhaus, and M. S. Dresselhaus, *Physical Properties of Carbon Nanotubes* (Imperial College Press, London, 1998).
[9] J. C. Coiffic, M. Fayolle, S. Maitrejean, L. E. F. Foa Torres, and H. Le Poche, Appl. Phys. Lett. **91**, 252107 (2007).
[10] W. Liang, M. Bockrath, D. Bozovic, J. H. Hafner, M. Tinkham, and H. Park, Nature (London) **411**, 665 (2001).
[11] F. Wu, P. Queipo, A. Nasibulin, T. Tsuneta, T. H. Wang, E. Kauppinen, and P. J. Hakonen, Phys. Rev. Lett. **99**, 156803 (2007); L. G. Herrmann, T. Delattre, P. Morfin, J.-M. Berroir, B. Placais, D. C. Glattli, and T. Kontos, *ibid.* **99**, 156804 (2007); N. Y. Kim, P. Recher, W. D. Oliver, Y. Yamamoto, J. Kong, and H. Dai, *ibid.* **99**, 036802 (2007).
[12] J. Kim, H. So, N. Kim, J. Kim, and K. Kang, Phys. Rev. B **70**, 153402 (2004); Z. Yu and P. Burke, Nano Lett. **5**, 1403 (2005); C. Meyer, J. Elzerman, and L. Kouwenhoven, *ibid.* **7**, 295 (2007); P. J. Leek, M. R. Buitelaar, V. I. Talyanskii, C. G. Smith, D. Anderson, G. A. C. Jones, J. Wei, and D. H. Cobden, Phys. Rev. Lett. **95**, 256802 (2005).
[13] C. Roland, M. Buongiorno Nardelli, J. Wang, and H. Guo, Phys. Rev. Lett. **84**, 2921 (2000).
[14] P. A. Orellana and M. Pacheco, Phys. Rev. B **75**, 115427 (2007).
[15] C. Wuerstle, J. Ebbecke, M. E. Regler, and A. Wixforth, New J. Phys. **9**, 73 (2007).
[16] M. Guigou, A. Popoff, T. Martin, and A. Crépieux, Phys. Rev. B **76**, 045104 (2007); G. Cuniberti, M. Sassetti, and B. Kramer, Phys. Rev. B **57**, 1515 (1998).
[17] L. Oroszlany, V. Zolyomi, and C. J. Lambert, e-print arXiv:0902.0753 (unpublished).
[18] Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).
[19] H. M. Pastawski, Phys. Rev. B **46**, 4053 (1992).
[20] A.-P. Jauho, N. S. Wingreen, and Y. Meir, Phys. Rev. B **50**, 5528 (1994); C. A. Stafford and N. S. Wingreen, Phys. Rev. Lett. **76**, 1916 (1996).
[21] L. Arrachea, Phys. Rev. B **72**, 125349 (2005).
[22] S. Kurth, G. Stefanucci, C. Almbladh, A. Rubio, and E. K. U. Gross, Phys. Rev. B **72**, 035308 (2005).
[23] A. Agarwal and D. Sen, J. Phys.: Condens. Matter **19**, 046205 (2007).
[24] M. Moskalets and M. Büttiker, Phys. Rev. B **66**, 205320 (2002).
[25] S. Camalet, J. Lehmann, S. Kohler, and P. Hänggi, Phys. Rev. Lett. **90**, 210602 (2003).
[26] L. E. F. Foa Torres, Phys. Rev. B **72**, 245339 (2005).
[27] B. J. Keay, S. Zeuner, S. J. Allen, Jr., K. D. Maranowski, A. C. Gossard, U. Bhattacharya, and M. J. W. Rodwell, Phys. Rev. Lett. **75**, 4102 (1995).
[28] P. K. Tien and J. R. Gordon, Phys. Rev. **129**, 647 (1963).
[29] L. Shi, J. Zhou, P. Kim, A. Bachtold, A. Majumdar, and P. L. McEuen, J. Appl. Phys. **105**, 104306 (2009).
[30] M. Strass, P. Hänggi, and S. Kohler, Phys. Rev. Lett. **95**, 130601 (2005).
[31] M. Moskalets and M. Büttiker, Phys. Rev. B **78**, 035301 (2008).