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An optical driven electromechanical transistor based on tunneling effect

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A new electromechanical transistor based on an optical driven vibrational ring structure has been postulated. In the device, optical power excites the ring structure to vibrate, which acts as the shuttle transporting electrons from one electrode to the other forming the transistor. The electrical current of the transistor is adjusted by the optical power. Coupled opto-electro-mechanical simulation has been performed. It is shown from the dynamic analysis that the stable working range of the transistor is much wider than that of the optical wave inside the cavity, i.e. the optical resonance enters non-periodic states while the mechanical vibration of the ring is still periodic.

OCIS Codes: (230.3990) Micro-optical devices, (230.4910) Oscillators.

The field of cavity optomechanics has been attracting many researchers to devote their efforts in both the theoretical and experimental investigations. Phenomena such as quantum entanglement [1], quantum manifestation [2], dynamical backaction [3], bistability [4], and optomechanical cooling [5] have been intensively researched. Due to the rapid advancement of the micro/nano-mechanical fabrication technology, various of optomechanical devices have been realized [6]. Many interesting experiments have been conducted, such as the motion of a thermal cloud of Cs atoms trapped inside an optical cavity was cooled by cavity optomechanics in [7], quantum-coherent coupling of a mechanical oscillator to an optical cavity mode has been achieved in [8], and this achievement has paved the way for establishing an efficient quantum interface between mechanical oscillators and optical photons. Based on the standard fabrication techniques, D. K. Armani et al. [9] have successfully fabricated ultra-high-Q (UHQ) silica toroid microcavity on a silicon chip, and it facilitated many experiments that relay on the UHQ cavities, such as the Tal Carmon group has conducted a series of experiments to investigate temporal behavior of radiation pressure (RP) induced vibrations, where chaotic quivering of the optical field has been found and analyzed [10]. Essentially, almost all previous research on the cavity optomechanics is based on the RP, which plays the key role for optomechanical coupling and can be described by quantum Hamiltonian formulation [11] [12]. The RP can be used to modulate the motions of mechanical structures. Strictly speaking, these mechanical motions are only about a few Å [10]. From the application point of view, especially in the sensing applications, the practical and critical concern is how to capture the motion, and it is anticipated to transfer the mechanical motions into electrical signals directly. Previously mass sensors based on electromechanical transistors have been demonstrated in [13] [14]. In this work, we explore to build a new electromechanical transistor device driven by the RP. The electromechanical transistor is based on mechanical vibrations of the optical cavity structure and quantum tunneling effect. The motivation of creating this device lies on the perfect match between displacements needed in the electromechanical transistors, normally in Å distance [15], and the vibrational amplitudes of the optical cavities. In this article a model of the device mentioned above has been described. The electrical current of the proposed transistor device is controlled by modulating the input continuous wave (CW) laser which acts like the 'gate' of the transistor. In this model, the UHQ cavity can not only operate in linear mode but also in nonlinear state. In the nonlinear operation regime, even though the intracavity optical field is in chaotic state, the electrical current flowing from source to drain is still linear, indicating that it has a very wide operation range, and this will have potential applications in areas such as sensing [16] and signal processing [17].

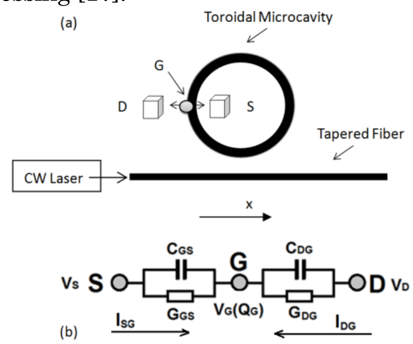

Fig. 1(a). Schematic graph of the transistor driven by a CW laser; Fig. 1(b): the equivalent circuit of the transistor device.

The design of the device is schematically shown in Figure 1. It consists of an Ultra-high-Q (UHQ) toroid cavity and a CW laser pump. The laser is coupled into the cavity by the fiber taper. There are two electrodes mechanically fixed in the vicinity of the cavity forming the drain D and source S. The gate electrode G, essentially a thin layer of metal is coated on the ring. Under the resonating optical power built in the cavity, the cavity will deform subject to the RP. This deformation, at the same time, causes the optical wave in the cavity deviate from the resonance thereby lowering the RP. Under the mechanical restoring force and the varying RP, the cavity will repeat the expansion and extraction process, behaving as a mechanical oscillator. The vibration amplitude of the oscillator depends on the input power of the CW laser. In such a dynamic system, under a DC voltage applied between S and D, the G will load some electrons from S and then unload them to D based on tunneling effect, known as the electron shuttling mechanism [18] [19], which is the principle of the electromechanical transistor. The equivalent circuit of the transistor is depicted in Figure 1b, where C_{GS} and C_{DG} are capacitance between terminals S and G, and G and D respectively. C_{G0} is the capacitance between the bead and ground. Q_G is the charge carried by the G, which varies with the displacement of the cavity. G_{GS} and G_{DG} are conductance between S and G, G and D respectively, which are functions of the cavity displacement, that is $G_{DG,GS} = G^0_{DG,GS} e^{(\mp x_1/\lambda)}$, where $G^0_{DG,GS}$ is the initial conductance. x_1 is the displacement of the cavity. λ is the tunneling length defined as $\lambda = \left(2\sqrt{2m_e\phi}/\hbar\right)^{-1}$. Here m_e is the mass of a single electron, $\hbar$ is the Planck constant divided by 2π, ϕ is the work function of the electrode. The dynamics of the Q_G, describing the charge on the G, can be expressed as [20]:

$$\dot{Q}_G = V_D G^0_{DG} e^{-x_1/\lambda} + V_s G^0_{GS} e^{x_1/\lambda} - V_G(Q_G) G_\Sigma \quad (1)$$

Where the voltage on G is a function of Q_G, and it is written as:

$$V_G(Q_G) = \frac{Q_G + V_D C_{DG} + V_S C_{GS}}{C_\Sigma} \quad (2)$$

and

$$\begin{aligned} C_\Sigma &= C_{DG} + C_{GS} + C_{G0} \\ G_\Sigma &= G^0_{DG} e^{-x_1/\lambda} + G^0_{GS} e^{x_1/\lambda} \end{aligned} \quad (3)$$

Apart from the electronic part, according to the previous work [21], it needs four dynamical variables (E_{re}, E_{im}, x_1, x_2) to describe the optical cavity and laser pump coupled system. They represent the real and imaginary components of the intracavity optical field ($E = E_{re} + iE_{im}$). It is noted that E is not the intracavity optical field itself but a slowly varying amplitude, which has been employed in references [10] [21]. (x_1, x_2) are the displacement and velocity of the cavity. These four variables are mathematically expressed as a set of equations in autonomous form [21]:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -ax_2 - bx_1 + c(E_{re}^2 + E_{im}^2) \\ \dot{E}_{re} &= (e - fx_1)E_{im} - dE_{re} \\ \dot{E}_{im} &= gE_p - (e - fx_1)E_{re} - dE_{im} \end{aligned} \quad (4)$$

The first two equations describe the motion of the cavity, which is seen as an oscillator and it is driven by the RP expressed in the form of $c({E_{re}}^2 + {E_{im}}^2)$. The third and fourth equations describe the dynamics of the intracavity field in the cavity. The optical field is detuned by the cavity displacement x_1, which is represented by the term of $(e - fx_1)E_{im,re}$. In equation (4), $a = \omega_m / Q_m$, $b = {\omega_m}^2$, $c = n/(c_0 \rho \pi r^2 R)$, $e = \omega_o - \overline{\omega}_o$, $d = \alpha c_0 / n$, $f = {\omega_o}^2 n/(c_0 N)$, $g = \sqrt{\alpha c_o / n\tau}$. ω_m is the frequency of the cavity. Q_m is the quality factor of the cavity. n is the refractive index, c_0 is the vacuum velocity of light, α is the absorption coefficient in cavity, ρ is the material density. R and r are the major and minor toroid radii respectively. ω_o is the frequency of the optical wave and $\overline{\omega}_o$ is the optical resonance at mechanical equilibrium. The number of optical wavelengths along the circumferential when resonating is represented by N. τ is the time that light takes to accomplish one round trip in the cavity. $|E_p|^2$ is the input power of the CW laser pump which can be used to modulate the vibrating mode of the cavity. In the calculation, $|E|^2$ and $|E_p|^2$ are normalized and take the unit of a.u. (dimensionless).

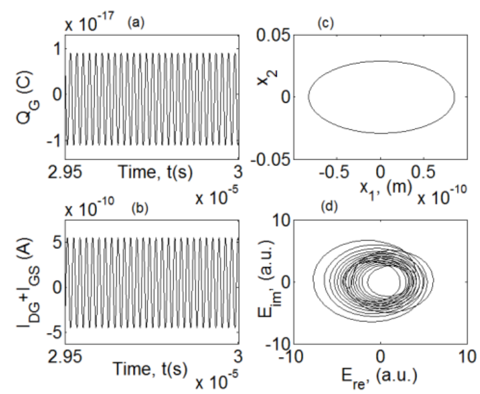

Fig. 2. Simulated opto-electromechanical transistor. a), Charge value at G terminal when the microcavity is oscillating periodically. b), Electrical current flowing through the terminals D and S. c), Plot of mechanical deformations x_1 and its velocity x_2 d), Plot of the real part E_{re} vs imaginary part E_{im} of the circulating optical mode.

We combine all the above equations and take the experimentally adjustable parameters [21] for simulation, a=1.4×10^6 Hz, b=1.2×10^17 Hz^2, c=9779 N*s, d=1.2×10^8 Hz, e=1.3×10^8 Hz, f=1.1×10^20 1/(s*m), g=2.2×10^10 1/s^2. The tunneling length λ is taken 0.5×10^-10 m. The initial conductance $G^0_{DG,GS}$ are all 1×10^-10 S. C_{GS} and C_{DG} are all 1×10^-18 F. C_{G0}=2×10^-18 F. The toroidal cavity we used here is taken from [10], where it has been experimentally realized. The major and minor of the toroid radii are 14.5 and 3 μm. The mechanical Q_m and optical quality factor Q_e are taken as 250 and 1×10^7 respectively. The metallic gate G is supposed to be a very thin film that has an ignorable effective mass comparing with the toroidal cavity. Thus it will not affect the mechanical resonance of the cavity. Meanwhile the optical quality factor is defined as $Q_e = \omega_e \tau 2\pi / l$, where l is fractional power loss. Obviously, the gate G will not have an effect on any variables in the definition of Q_e. I_{DG} and I_{SG} are defined as currents flowing from D to G, and from S to G respectively. Results of the numerical calculation from equation (4) when applying DC voltage V_{DS}=16 V and the input power E_p=0.2 are shown in Figure 2, in which it is seen that the Q_G in (a) and $I_{DG}+I_{SG}$ in (b) versus time are all shuttling periodically with approximately 60 electrons per cycle. We have plotted x_1 versus x_2 in Figure 2(c), in which there is a single circle meaning the motion of mechanical cavity is in single period/frequency. While in Figure 2(d), the plot of E_{re} versus E_{im} is performing multi-period motions as more complicated circles are shown. We keep V_{DS}=16V unchanged but increase the input power E_p to 1, and the results are shown in Figure 3. In the Figure 3(a), it is shown that the Q_G has changed to quasi-periodic with about 193 electrons being shuttled per cycle. That is because, under a higher input optical power, the vibration amplitude of the cavity has increased which leads to an enhanced tunneling effect. The similar pattern of $I_{DG}+I_{SG}$ versus time is plotted in Figure 3(b). Meanwhile we have plotted the 3-dimentional projection of the optical dynamic system (E_{im} and E_{re}) according to equation (4) in Figures 3(c) and 3(d), where a chaotic attractor is displayed in 3(c), and a non-chaotic attractor is shown in 3(d) when E_p = 0.2. Furthermore, we calculated the Lyapunov exponents of the equation (4), it is seen in Figure 3(e) that the largest exponent λ_1 >0, which proves that the optical field (E_{im} and E_{re}) is in chaotic state. We have calculated the threshold at which the shuttling phenomenon starts with varying input power E_p from 0.005 to 0.4 in Figure 4, and it is seen from the Figure 4 that the shuttling begins at E_p=0.025 but with very weak tunneling while as Ep increased we see the maximum Q_G is increased. The range between E_p=0.21 to E_p=0.345 is the best operating range as the transported charge Q_G is more stable. Q_G is directly related to the displacement x_1. Higher E_p values cause the optical resonance to exhibit multi-periodic and eventually chaos, but the peak amplitude of the RP no longer increases. Therefore x_1/Q_G will saturate at a threshold E_p. Finally we calculated the average current I_a that flows from the source to drain with varying potential between V_D and V_s in Figure 5. The upper line is the case when the optical field is in the chaotic state (E_p=1) and the lower line is calculated at E_p=0.2 at which the optical field is in the period state. It is interesting to find that both the two states have a linear curve even when the system driven at high input power. It is found from the simulation results that the electromechanical transistor system has a much wider stable range than the optical resonating system in the cavity. This is interpreted as follows. At high input optical power, the optical wave inside the cavity has been driven into the chaotic state by the large mechanical vibration amplitude of the cavity. However the chaotic optical field inside the cavity cannot drive the mechanical structure into non-periodical regions due to the small quality factor of the mechanical structure compared to very large optical quality factor, as well as the large mechanical restoring force. In other words, the mechanical cavity structure functions as a filter damping out all optical oscillations except for the oscillation at the mechanical resonant frequency. In the meantime the mechanical vibration still drives the optical field into non-periodic states. This phenomenon is actually advantageous in the proposed transistor device, as the device is able to work in a much wider input optical power range despite the optical filed inside the cavity already displays non-stable vibrations.

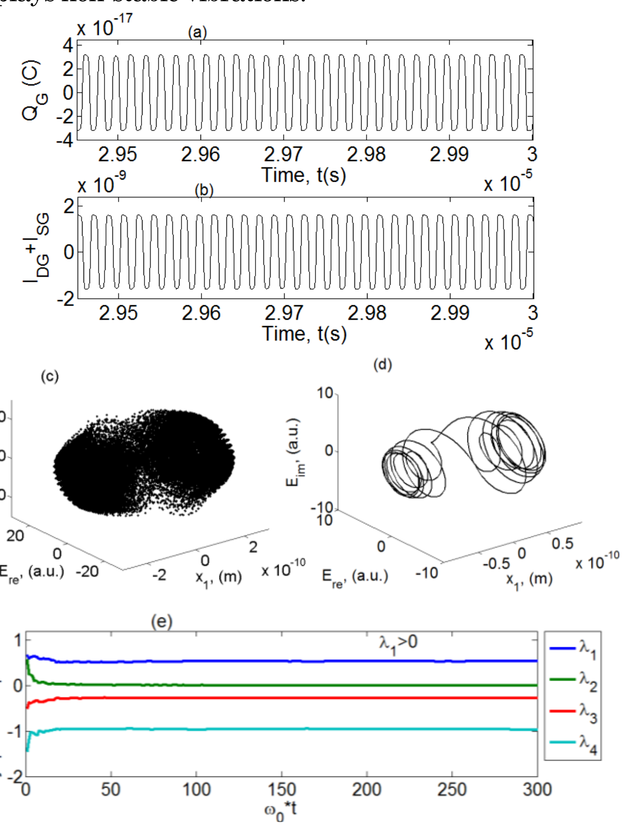

Fig. 3a. Charge value at G terminal when the microcavity is oscillating in the chaotic state. Fig. 3b. Electrical current flowing through terminals D and S. Fig. 3c. Calculated chaotic attractor. Fig. 3d. Calculated 3D projection of the optical dynamic system at non-chaotic state. Fig. 3e. Lyapunov exponents of the system when pump power E_p=1.

In conclusion, a new electromechanical transistor device operated by optomechanical cavity has been proposed and subsequently modeled. The coupled opto-mechanical-electronic simulation has validated that the device is able to work as a transistor device controlled by the optical RP. Nonlinear analysis of the mechanical vibrations under large driving power has also been analyzed. The results conclude that the transistor device has a much wider working range compared with the optical field inside the cavity, which has been elucidated from the viewpoints of the mechanical properties of the cavity.

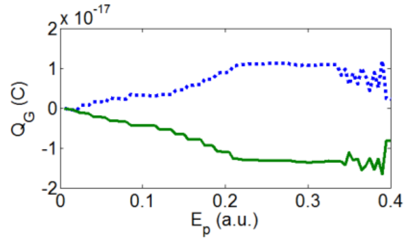

Fig. 4. Calculated threshold pump power E_p of opto-electromechanical transistor.

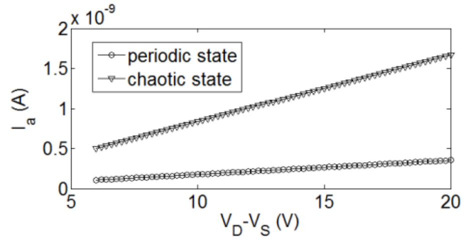

Fig.5. Average current I_a versus applied DC voltage between drain and source (V_D-V_S). The upper line is for the optical wave in the chaotic state and the lower one is for the optical wave in the linear state.

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