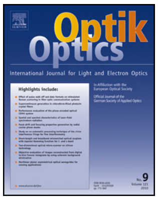
Optik 159 (2018) 368–378

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Original research article

Enhanced mechanical entanglement in an optomechanical cavity with a Coulomb interaction

X. Hu, B.P. Hou*, B. Tang

College of Physics and Electronic Engineering, Institute of Solid State Physics, Sichuan Normal University, Chengdu 610101, People's Republic of China

ARTICLE INFO

Article history:
Received 31 December 2017
Accepted 21 January 2018

Keywords:
Two-coupled-mechanical-mode optomechanical cavity
Mechanical entanglement
Coulomb interaction

ABSTRACT

A scheme of a two-mode optomechanical cavity is proposed to investigate the entanglement between two nanomechanical resonators which are coupled by a Coulomb interaction. It is found that the mechanical entanglement can be improved by the Coulomb coupling, and the restriction of environment temperature on the entanglement can be relaxed by strengthening the Coulomb coupling. Additionally, the optomechanically induced transparency in the present scheme can provide a wider transparency frequency range in which the mechanical entanglement is created. The scheme of the enhanced entanglement by the Coulomb interaction is of more convenient controllability only by adjusting the bias gate voltage.

1. Introduction

A usual optomechanical cavity is composed by a fixed mirror and a movable mirror which is coupled to the optical field in the cavity by the radiation pressure [1]. The optomechanical system (OMS) has many important applications in quantum optics and information science, such as the stationary entanglement [2,3], the optomechanically induced transparency (OMIT) [4–6], the detection with ultrahigh precision [7,8], the transition between classical and quantum behavior [9–11], the cooling of micromechanical motion to the quantum ground state [12–14], and the nonlinearity [15–17].

Quantum entanglement, as a very important resource in quantum information processing, has many applications, such as in quantum computation, quantum communication [18]. In recent years, much attention has been paid to studying the various quantum entanglements in the OMS. The stationary entanglement between an optical cavity field mode and a macroscopic vibrating mirror generated by means of radiation pressure has been investigated [3]. Subsequently, the entanglement between the two optical modes via the optomechanical interfaces has been studied [19,20]. On the other hand, the entanglement between two mechanical modes has attracted much attention. For example, the entanglement between two vibrations suspended inside a Fabry-Perot cavity was considered [21]. The entanglement between two nanomechanical resonators (NRs) in a ring cavity by feeding squeezed light was investigated [22]. A scheme for entangling two spatially remote mechanical devices by means of the entanglement swapping was presented [23]. The stationary entanglement between two vibrational modes of the mirrors driven by an intense classical laser field was studied [24], and stationary entanglement between one charged nanomechanical oscillator in the optomechanical cavity and another charged oscillator

---

* Corresponding author.
E-mail address: bphou@sicnu.edu.cn (B.P. Hou).

https://doi.org/10.1016/j.ijleo.2018.01.072

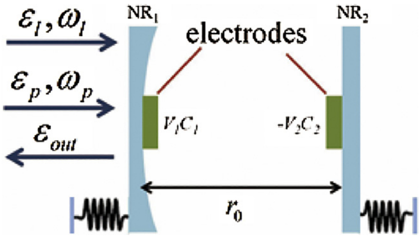


Fig. 1. Sketch of the optomechanical cavity with two NRs coupled by Coulomb interaction. NR1 is charged by the bias gate voltage V_1 and NR2 by the bias gate voltage $-V_2$. The NR1 is simultaneously driven by the pump field ε_l with frequency ω_l, and the probe filed ε_p with frequency ω_p entering the cavity through the partially transmitting mirror. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

induced by the Coulomb interaction was investigated [25]. Also, it was shown that the stationary entanglement between two mirrors in a double-cavity driven by squeezed light can be generated [26].

As is well known that the quantum properties can be weakened by the absorption induced by the system's surrounding. In particular, the entanglement between the two mechanical modes in the present scheme relies intensely on the absorption in the cavity field, which will be displayed in the following section. Therefore, we shall investigate the absorption properties of the cavity field to wonder that there appears a small absorption or transparency in the entanglement region. It is shown that the field absorption in the OMS can be suppressed by the optomechanically induced transparency (OMIT) resulted from the destructive interference between the probe field and anti-Stokes scattering induced by the radiation pressure [5]. Recently, the study on the OMIT has been generalized from the single optomechanical cavity to two or more optical or mechanical-mode optomechanical systems. For example, the OMIT in the two-cavity-mode optomechanical system was theoretically demonstrated [27–30], and the OMIT was addressed in the two-mechanical-mode optomechanical systems, which are realized by the mechanical interaction between the two oscillators [31–33]. Additionally, the OMIT in the optomechanical systems with the linear coupling between the optical field and the mechanical mode has been generalized to the quadratically coupled optomechanical systems, in which the optical cavity field is coupled parametrically to the square of the position of the mechanical oscillator [34,35]. The OMIT has many applications, such as in superluminal and ultraslow light propagation [36,37], and in the precision measurement of electrical charge [38].

The generation and enhancement of the mechanical entanglement in the proposed schemes have strict requirements and rely on the optomechanical coupling or the squeezed light. Meanwhile, the entanglement is fragile with the influence of temperature. In the present paper, we propose a scheme for enhancing the mechanical entanglement between the two NRs in the two-mechanical-mode optomechanical cavity, in which the two NRs are coupled by the Coulomb interaction between the charged electrodes loaded on the two oscillators. We find that the entanglement between the two NRs can be improved by the Coulomb interaction, then the restriction of environment temperature on the entanglement can be relaxed by strengthening the Coulomb coupling. The mechanical entanglement generated in the present scheme is of more convenient controllability only by adjusting the bias gate voltage. On the other hand, we consider the OMIT in the entanglement region to reduce the optical absorption which suppresses the entanglement.

This paper is organized as follows. In Section 2, we present the model and give the quantum Langevin equations of the system. In Section 3, we analyze the effects of the pump power, the Coulomb interaction and the temperature of the environment on the entanglement between the two NRs. Subsequently, we study the OMIT in this system in Section 4. A brief conclusion is presented in Section 5.

2. Mode and dynamical equation

The optomechanical system under our consideration, which is sketched in Fig. 1, is composed by two NRs. The two NRs constitute a cavity with optical mode c, of which the resonance frequency and decay rate are denoted by ω_c and κ, respectively. The left NR1 is simultaneously driven by a strong coupling field $\varepsilon_l = (2\wp_l\kappa/\hbar\omega_l)^{1/2}$ with frequency $\omega_l = 2\pi c/\lambda_0$ (λ_0 is the wavelength) and a weak probe field $\varepsilon_p = (2\wp_p\kappa/\hbar\omega_p)^{1/2}$ with frequency ω_p, in which $\wp_i$ ($i = l, p$) denotes its power. Additionally, the NR1 with frequency ω_1 and effective mass m_1 is charged by the bias gate voltage V_1, and the NR2 with frequency ω_2 and effective mass m_2 is charged by the bias gate voltage $-V_2$. The two NRs, which take the charges V_1C_1 and $-V_2C_2$ with C_1 and C_2 being their capacitances, are coupled each other by the Coulomb interaction. And q_i and p_i ($i = 1, 2$) are the small displacements and momentum operators of the charged NRs. The Coulomb coupling part is given by $G = \frac{-C_1V_1C_2V_2}{4\pi\varepsilon_0|r_0+q_1-q_2|}$ where r_0 is the equilibrium distance between NR1 and NR2. Under the assumption of $r_0 \gg q_1, q_2$ the Coulomb coupling part can be expanded to the second-order as $G \approx \frac{-C_1V_1C_2V_2}{4\pi\varepsilon_0 r_0}\left[1 - \frac{q_1-q_2}{r_0} + \left(\frac{q_1-q_2}{r_0}\right)^2\right]$. After dropping the