Theory of the strong phonon-photon coupling in an optical fiber taper

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In the last few years, the field of cavity optomechanics, a new branch of physics which focusses on the interaction between light and small mechanical objects, has drawn widespread interest because of fundamental observations such as Rabi oscillations and optomechanically-induced transparency[1]. Here, we theoretically investigate the interaction between light and a sub-wavelength silica optical fiber and demonstrate that strong phonon-photon coupling can also be achieved under high optical power, giving rise to Rabi oscillations.

Let us first describe the photon-phonon interaction under consideration as that shown in Fig. 1(a). When coherent laser light (red) is coupled and guided into an optical fiber taper, it generates via electrostriction an acoustic wave (green) that acts as a moving Bragg reflector. Light is thus scattered in the backward direction by this moving index grating, giving rise to a Stokes wave (blue) down frequency shifted by an amount that corresponds to the phonon frequency. Furthermore, the coherent interaction between the pump and Stokes generates an optical beating (purple) that propagates at the same speed as the phonon (5900 m.s^{-1} in silica).

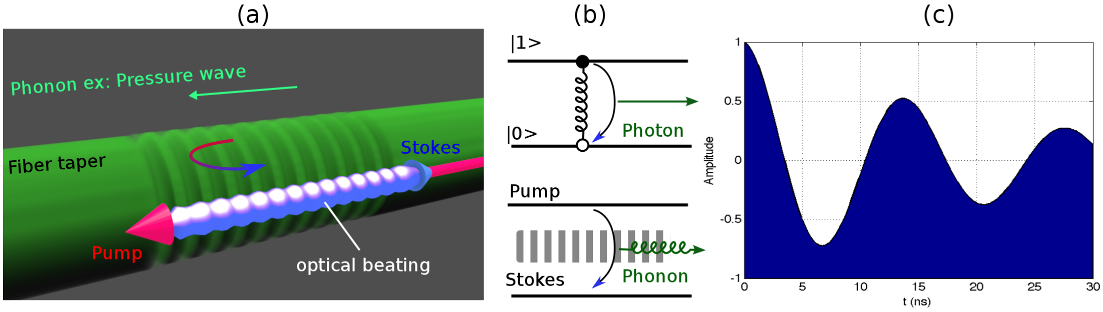

Fig. 1 Schematic of the photon-phonon Brillouin interaction in a fiber taper. (b) Comparison between the exciton-polariton picture and our photon-phonon interaction. (c) Rabi oscillations due to the strong coupling regime in a 700-nm diameter silica nanofiber. Pump and Stokes power are 200 W and 1mW, respectively.

In the quantum picture, a pump photon (P) is annihilated to create both a Stokes photon (S) and an acoustic phonon, as shows the bottom of Fig. 1(b). Contrary to the Rabi problem, the resonant frequency and transition energy is here not determined by the two levels P and S but by the phonon. Since the phonon describes the acoustic vibration of the taper, it has discrete resonant frequencies like a fixed spring. On the opposite, the two optical P and S waves can be translated in frequency. To observe Rabi oscillations in such a system, it is required to get a sufficiently strong coupling to transfer the energy back and forth between the optical beating and the phonon over the phonon lifetime (10 ns). As a result, high optical power is needed. Moreover, we need to only excite one guided acoustic mode using sub-wavelength optical fiber. From the Boyd's model[4] of Brillouin scattering and the Poynting theorem, we can show that the interaction between the phonon ρ and the optical beating between the pump and Stokes waves is governed the following two coupled differential equations

$$\frac{\partial \rho}{\partial t} + \frac{\Gamma_B}{2}\rho + v_a \frac{\partial \rho}{\partial z} = i\,\frac{\beta_a^2}{2}\frac{\epsilon_0 \gamma_e}{\Omega_a}\frac{1}{A_{eff}} A_p A_s^* \qquad \text{and} \qquad \frac{\partial A_s A_p^*}{\partial z} + \frac{1}{v_b}\frac{\partial A_s A_p^*}{\partial t} = -i2\omega_p \omega_s \frac{\gamma_e \rho^*}{c\rho_0}\left(\frac{A_s A_s^*}{\omega_s} - \frac{A_p A_p^*}{\omega_p}\right),$$

Solving these equations in the reference frame of the phonon velocity, we find that this system can be strongly coupled when the beating propagates at the same speed as the photon (v_b=v_a). Providing that the *population inversion* in the right-hand side of the first equation is constant, we get two coupled equations whose eigenvalues oscillate at Rabi frequency. Figure 2(b) shows the resulting amplitude of the optical beating at a high pump power of 200W and a Stokes power of 1mW. As expected, we can clearly see Rabi oscillations with positive and negative amplitudes. The damped oscillations are actually intensity fluctuations of the optical beating, as shown by the blue area in Fig. 2(b).

To conclude, we have theoretically investigated the conditions to observe the strong phonon-photon coupling and Rabi oscillations using Brillouin scattering in a submicron silica optical fiber taper.

References

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