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TOPICAL REVIEW — Solid-state quantum information processing

Cavity optomechanics: Manipulating photons and phonons towards the single-photon strong coupling*

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Cavity optomechanical systems provide powerful platforms to manipulate photons and phonons, open potential applications for modern optical communications and precise measurements. With the refrigeration and ground-state cooling technologies, studies of cavity optomechanics are making significant progress towards the quantum regime including nonclassical state preparation, quantum state tomography, quantum information processing, and future quantum internet. With further research, it is found that abundant physical phenomena and important applications in both classical and quantum regimes appeal as they have a strong optomechanical nonlinearity, which essentially depends on the single-photon optomechanical coupling strength. Thus, engineering the optomechanical interactions and improving the single-photon optomechanical coupling strength become very important subjects. In this article, we first review several mechanisms, theoretically proposed for enhancing optomechanical coupling. Then, we review the experimental progresses on enhancing optomechanical coupling by optimizing its structure and fabrication process. Finally, we review how to use novel structures and materials to enhance the optomechanical coupling strength. The manipulations of the photons and phonons at the level of strong optomechanical coupling are also summarized.

Keywords: optomechanical systems, single-photon strong coupling, controllable photons and phonons transport

PACS: 42.50.Wk, 42.82.Fv, 42.65.Sf, 42.79.Nv **DOI:** 10.1088/1674-1056/27/2/024204

1. Introduction

High quality-factor optical and mechanical modes can be coupled to each other through the radiation pressure. The cavity field localization results in a stronger optomechanical interaction, compared to that of a traveling light wave impacting on the macroscopic objects.[1] At the mesoscale, the eigenfrequencies of the cavity modes are sensitive to the variation of the effective cavity length, depending on the position of the movable mirror, which is modeled as a mechanical resonator. Based on these two aspects, modern cavity optomechanics mainly explores the interactions between the cavity field and the mechanical mode.[2] Any system, in which the mechanical motion gives a backaction on the dynamics of the cavity field (e.g., dissipation of the cavity fields) and vice versa, can be considered as a generalized optomechanical coupling system, and be included in the modern cavity optomechanics.[3]

Typical microcavities of the cavity optomechanical systems (COMS) are formed by, for example, Fabry–Pérot mirrors, whispering-gallery, photonic-crystal system or LC-oscillators. Although the geometric shapes of these cavities are different, the theoretical models, describing the optomechanical coupling, always have the same expression with the radiation pressure interaction. Here, the optical force is proportional to the intracavity photon number, which can be controlled by the power of the external control field.[4] When the power of the control field is strong enough, the optomechanical coupling can be linearized, and the optomechanical coupling strength, called as effective optomechanical coupling strength, can be enhanced by the control field. From then on, the COMS becomes a powerful platform to manipulate cavity field (photons) and mechanical motion (phonons), and is also applied for on-chip optical interconnect, precise measurement, and quantum information processing.[5–8]

In the classical regime, based on the linearized optomechanical coupling, many experiments have been devoted to studying cavity-optomechanically induced transparency (COMIT), which is similar to electromagnetically induced transparency (EIT), observed in atomic systems. The COMIT usually is from destructive interference between two different excitation pathways. This can be used to control light propagation on a chip, and to produce slow and fast light.[9] It even enables the complete stop or on-chip storage of the propagating light pulse via microfabricated optomechanical arrays.[10–16] Recently, optomechanical interac-

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tions are proposed to strongly break the reciprocity of light propagation. This motivates extensive study of magnetic-free and low-loss nonreciprocal devices,[17–19] such as optical isolators,[20–27] circulators,[28–32] and nonreciprocal phase shifter.[33] The nonreciprocal conversions between microwave and optical photons with optomechanical interaction are also explored for signal routing and protection.[34–36] Besides the control of classical light transmission, the optomechanical interaction can also be used to manipulate the mechanical properties, for example, controlling the phononic structures[37] and shifting mechanical frequency or decay rate by optical force.[38–40] Similar to the nonreciprocal light propagation, the optomechanical interaction can also induce a nonreciprocity of the mechanical motion (or called a sound wave).[41,42] Thus, the cavity optomechanical systems are powerful platforms to realize acoustic nonreciprocal devices,[43,44] such as sound isolators and acoustic circulators. By introducing multi-mode optomechanical interactions, e.g., two optical modes interacting with the same mechanical mode, one can achieve chiral cooling,[45] as well as phonon routing.[46,47] In particular, the mechanical resonator can be simultaneously coupled to optical and electronic cavities. This can be used for wideband wavelength conversion and energy transfer between microwave and optical fields.[48–57]

In the quantum regime, the linearized optomechanical systems have been used to generate nonclassical states for both the optical and mechanical modes. For example, it was recognized that cavity optomechanical systems can be used to generate squeezed light, which is closely related to quantum-limited displacement sensing,[58,59] owing to proposals for increasing the displacement sensitivity of large scale gravitational-wave observation with squeezed light.[60–65] Because the equivalence between an optomechanical system and Kerr systems,[66,67] the mechanism for generating squeezed light in optomechanics[68–71] is similar to that studied in Kerr nonlinear medium.[72,73] Recent researches show great interests in engineering a squeezed state of the macroscopically moving object,[74] i.e., squeezing the mechanical motion at large scales.[75,76] These are related to the study of decoherence of macroscopic quantum systems and the realization of ultrasensitive sensing of force and motion.[77] A crucial step for quantum manipulation of the macroscopic mechanical resonators is to cool the mechanical mode to its quantum ground state, in which the thermal noise is greatly reduced. Theoretical and experimental works show that the resolved sideband approach is a promising way to realize ground-state cooling.[78–96] In an opposite way, the optomechanical interaction can also be used to amplify the mechanical oscillation,[97–102] and generate phonon lasing with nonclassical phonon correlation.[103] The quantum-optical-control techniques are used to conditionally generate single-phonon Fock states of the mechanical resonator.[104] The nonclassical nature of these phonon states is verified by performing a Hanbury Brown and Twiss-type experiment without requiring full state reconstruction. Optomechanical interaction can also simultaneously modulate the optical field and the mechanical motion, for example, creating an entanglement between the mechanical oscillator and the cavity field.[105] The non-classical correlations between single-photons and -phonons from an optomechanical system were reported. These realize a full quantum protocol involving initialization of the resonator in its quantum ground state of motion and generation of correlated photon-phonon pairs.[106] Very recently, a cross-correlation technique was used to distinguish optically driven motion from thermally driven motion. This allows us to observe the quantum backaction up to room temperature.[107] The mechanical mode can interact simultaneously with two electromagnetic cavity modes with different wavelengths, (e.g., optical wave and microwave), and be used for the storage and transfer of a quantum state with high fidelity.[108–114] Fundamentally, the mechanical resonator can be optomechanically coupled to any electromagnetic mode in a wide frequency range.[115–119] Thus, the coherent-quantum-state transfer via optomechanical coupling allows one to overcome intrinsic limitations of both microwave and optical platforms.[120–122] These findings are very important for the study of exciting physics (e.g., quantum phenomena of macroscopic objects) and preparation of new generation quantum devices for applications in the real world.[123]

The studies reviewed above are mainly based on the linearized optomechanical coupling. Recently, much more attention has been paid to the nonlinear optomechanical coupling, which is a typical attribute of the cavity optomechanical systems.[124–126] Based on the optomechanical nonlinearity, manipulations of the optical field and the mechanical motion are widely studied for generating optical bistability[127–130] or multi-stability,[131–136] realizing chaotic optical fields with blue-sideband pumping,[137–139] slowing light with a high-order sideband.[140–152] For the manipulations of the mechanical resonator, the optomechanical nonlinearity has been explored to observe the stochastic resonance phenomenon and the chaos transfer between two optical fields.[153] When three-body interaction is considered, e.g., two mechanical modes are coupled to the same optical mode, these two indirectly coupled mechanical oscillators can be synchronized.[154–168] In the quantum regime, nonlinear optomechanical coupling strength is a key parameter for preparing nonclassical states of photons[169–171] and phonons.[172–177] Theoretical works reveal that optical antibunching[178–183] and photon blockade[184–188] can be observed in the single-photon strong optomechanical coupling regime, where the nonlinear optomechancial coupling strength

is larger than the decay rates of both the cavity field and the mechanical mode. This is also required when other nonclassical states (e.g., NOON state) are engineered in optomechanical systems.[189–200] There are many studies for fundamental physics under the strong coupling condition, including, e.g., the observations of phonon number jump[201–203] and phonon-phonon Josephson effect.[204,205] Motivated by the importance of strong coupling for the single-photon optomechanics, great efforts have been made to achieve strong optomechanical coupling. However, it is still a great challenge for experiments. In this article, we will review the mechanism that was theoretically proposed and experimentally studied to enhance the single-photon optomechanical coupling strength for the COMS. We hope that the works, summarized here, could motivate more fantastical ideas and experimental improvements to achieve strong optomechanical coupling in the future.

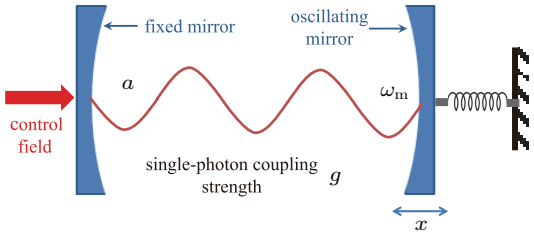


Fig. 1. (color online) Schematic diagram for the COMS with laser driving. The Fabry–Pérot cavity consists of two mirrors with high-reflectivity. The left mirror is fixed and the right one is movable, which is modeled as the mechanical resonator. The optical-force induced mirror movement changes the cavity length and in turn induces dispersions for the cavity fields. The single-photon optomechanical coupling is g, and the mechanical frequency is ω_m. x denotes displacement of movable mirror.

The paper is organized as follows. In Section 2, we describe the basic model and corresponding Hamiltonian of COMS. In Section 3, we review several methods theoretically proposed for enhancing optomechanical coupling strength. In Section 4, we review the progresses on enhancing optomechanical strength in conventional optomechanical systems by optimizing its structure and the fabrication process. We also review how to use novel structures and materials to enhance optomechanical coupling strength in Section 4. The manipulations of the photons and phonons with the improvement of optomechanical coupling strength are also summarized in corresponding sections in this section. A summary of single-photon coupling strength of different types of optomechanical systems and future perspectives is given in Section 5. Finally, we conclude the work in Section 6.

2. Theoretical model

As schematically shown in Fig. 1, the typical COMS is formed by a Fabry–Pérot (FP) cavity in which one mirror is fixed, and the other one is movable. For convenience, we assume that the left mirror is fixed, and the right mirror oscillates. The oscillating mirror supports the mechanical mode, which is optomechanically coupled to the cavity field. The system Hamiltonian is given as

$$H = H_{\rm free} + H_{\rm int}, \tag{1}$$

where $H_{\rm free}$ is the free Hamiltonian of the cavity field and mechanical resonator with the formalism

$$H_{\rm free} = \hbar\omega_{\rm c} a^{\dagger}a + \hbar\omega_{\rm m} b^{\dagger}b. \tag{2}$$

Here, a ($a^{\dagger}$) is the annihilation (creation) operator of the cavity field with eigenfrequency $\omega_{\rm c}$. b ($b^{\dagger}$) is the annihilation (creation) operator of the mechanical mode with eigenfrequency $\omega_{\rm m}$. The commutation relations for operators a and b satisfy $[a,a^{\dagger}]=1$, $[b,b^{\dagger}]=1$, $[a,b]=0$, and $[a,b^{\dagger}]=0$. We assume that m is the effective mass of the mechanical resonator, the displacement operator x of the mechanical resonator can be presented as $x = x_{\rm ZPF}(b^{\dagger}+b)$, where $x_{\rm ZPF} = \sqrt{\hbar/2m\omega_{\rm m}}$ is the zero-point fluctuation.

Because the displacement of the right mirror (mechanical resonator) is much smaller than the cavity length, the cavity frequency modulated by the position of the movable mirror can be treated with Taylor expansion, that is

$$\omega_{\rm c}(x) = \omega_{\rm c}(0) + \frac{\partial\omega}{\partial x}x + \frac{1}{2}\frac{\partial^2\omega}{\partial x^2}x^2 + \cdots. \tag{3}$$

Here, we only need consider the first order of Eq. (3), in this case the frequency shift of the cavity field due to the mechanical resonator is given by

$$\Delta\omega = \frac{\partial\omega}{\partial x}x. \tag{4}$$

The Hamiltonian $H_{\rm int}$ describing optomechanical coupling is written as

$$H_{\rm int} = \hbar g a^{\dagger}a(b+b^{\dagger}), \tag{5}$$

where $g = (\partial\omega/\partial x)x_{zpf}$ represents the single-photon optomechanical coupling strength. Finally, the full Hamiltonian of the typical optomechanical system is written as

$$H = \hbar\omega_{\rm c}a^{\dagger}a + \hbar\omega_{\rm m}b^{\dagger}b + \hbar g a^{\dagger}a(b^{\dagger}+b). \tag{6}$$

A detailed derivation of the Hamiltonian for optomechanical coupling can be found in Ref. [206]. We note that here we only focus on the optical radiation pressure force and the optical gradient force (always called as dispersive optomechanical interaction). The dissipative modulated or optothermally and piezoelectrically induced optical force can also be included in the general cavity optomechanical systems.

Applying a unitary transform $U = \exp[-ga^{\dagger}a(b^{\dagger}+b)]$ to Eq. (6), we can obtain an effective Hamiltonian $H_{\rm eff} = UHU^{\dagger}$ with

$$H_{\rm eff} = \hbar\omega_{\rm m}b^{\dagger}b + \hbar\left(\omega_{\rm c} - \frac{g^2}{\omega_{\rm m}}\right)a^{\dagger}a - \hbar\frac{g^2}{\omega_{\rm m}}a^{\dagger}a^{\dagger}aa. \tag{7}$$

which has eigenvalues

$$E_{m,n} = \hbar\left(n\omega_{\rm c} - n^2\frac{g^2}{\omega_{\rm m}}\right) + \hbar m\omega_{\rm m}, \tag{8}$$

corresponding to the eigenstates $|n,\tilde{m}\rangle = U|n,m\rangle$. Here, $|n,m\rangle$ represents a state with n photons and m phonons. From the above equation, we can see that the COMS is inherently nonlinear and the energy levels of the whole system are nonharmonic. Thus, the COMS is a promising platform to engineer non-classical states for both photons and phonons, as well as qubits for quantum information processing and measurement. Equation (8) also shows that the single-photon optomechanical coupling strength is a key parameter for nonlinear energy splitting. Thus, engineering such nonlinear optomechanical interaction has become very important. Below we will review the progresses in this research direction and related applications for manipulating cavity field and mechanical mode.

3. Theoretical proposals for enhancing the single-photon optomechanical coupling

To explore the quantum nonlinear behavior of optomechanics, the effects of the radiation pressure interaction should be observed at the single-photon level. This requires that the single-photon optomechanical-coupling strength g exceeds the cavity decay rate κ. Here we review several theoretical proposals to enhance optomechanical coupling strength for potential applications, such as nonclassical photon (phonon) state preparation, single-photon source, and the quantum state reconstruction.

3.1. $\mathcal{PT}$-symmetry enhanced optomechanical coupling

The system with $\mathcal{PT}$-symmetric Hamiltonian was originally explored at a highly mathematical level.[207] It is now realized and studied in physical systems, especially in coupled cavities that have balanced loss and gain.[208–211] In $\mathcal{PT}$-symmetric systems, the eigenvalues of non-Hermitian Hamiltonian coalesce and become real numbers at an exception point, which is also called the phase transition point. Around this point, there are two parameter regimes (i) The $\mathcal{PT}$-symmetry regime, where the real parts of the eigenvalues (representing the eigenfrequencies) are different, the imaginary parts (representing the linewidths) are the same. In particular, the imaginary parts are zero when gain and loss are balanced. (ii) The broken $\mathcal{PT}$-symmetry regime, where the real parts of the eigenvalues are the same but the imaginary parts are different. The typical behavior for the $\mathcal{PT}$-symmetric systems is a phase transition from $\mathcal{PT}$-symmetry to broken $\mathcal{PT}$-symmetry. Recently, the phase transition and field localization have been observed in such $\mathcal{PT}$-symmetric systems.[212,213] The energy localization originates from the optical nonlinearity and in turn greatly enhances this nonlinearity. This motivates researchers to enhance the single-photon optomechanical coupling near the point of phase transition in $\mathcal{PT}$-symmetric systems. Hereafter, we call the cavity with gain (loss) an active (passive) cavity.

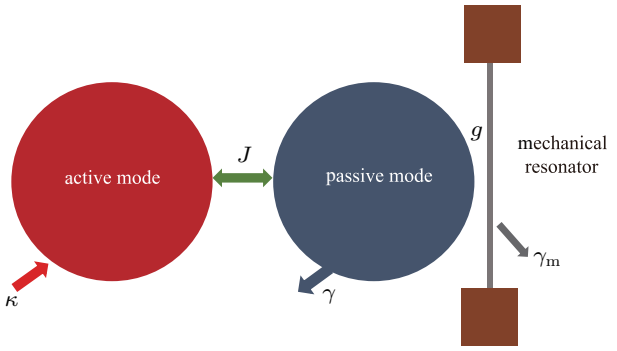


Fig. 2. (color online) Schematic diagram for the $\mathcal{PT}$-symmetric optomechanical systems. An active cavity with gain κ is coupled to a passive cavity with decay rate γ, where J represents the coupling strength between two cavity fields. Here, g is the optomechanical coupling strength between the passive cavity and the mechanical resonator with a decay rate $\gamma_{\rm m}$.

Considering a mechanical resonator optomechanically coupled to the optical field of the passive cavity in $\mathcal{PT}$-symmetric systems, as schematically shown in Fig. 2, we can write out the Hamiltonian for this $\mathcal{PT}$-symmetric optomechanical system:

$$\begin{aligned} H \;=\; & \hbar(\omega - {\rm i}\kappa)a^\dagger a + \hbar(\omega + {\rm i}\gamma)c^\dagger c + \hbar J\left(a^\dagger c + c^\dagger a\right) \\ & + \hbar\omega_{\rm m} b^\dagger b + \hbar g a^\dagger a(b^\dagger + b). \end{aligned} \tag{9}$$

Here, a, c, and b are annihilation operators for the passive cavity, active cavity and mechanical modes, respectively. $a^\dagger$, $c^\dagger$, and $b^\dagger$ are corresponding creation operators. The decay rate for the passive optical mode a is κ, and the gain rate for the active mode is γ, where J represents the coupling strength between two optical fields. The parameter g represents the single-photon optomechanical coupling strength. Note that two optical modes have been assumed to have the same frequency ω.

The Hamiltonian in Eq. (9) without the term $\hbar g a^\dagger a(b^\dagger + b)$ describes the $\mathcal{PT}$-symmetric system with an effective Hamiltonian:

$$H_{\rm PT} = \hbar(\omega - {\rm i}\kappa)a^\dagger a + \hbar(\omega + {\rm i}\gamma)c^\dagger c + \hbar J\left(a^\dagger c + c^\dagger a\right). \tag{10}$$

Rewriting Eq. (10) in a matrix form as used in Refs. [214] and [215], we obtain

$$H_{\rm PT} = \begin{bmatrix} r{\rm e}^{{\rm i}\theta} & J \\ J & r{\rm e}^{-{\rm i}\theta} \end{bmatrix}, \tag{11}$$

where $r = \sqrt{\omega^2 + \kappa^2}$ and $\theta = \arctan(\kappa/\omega)$. The eigenvalues of $H_{\rm PT}$ are

$$\lambda_\pm = r\cos\theta \pm \sqrt{J^2 - r^2\sin^2\theta}, \tag{12}$$

with the corresponding eigenvalues

$$|\Psi_+\rangle = \begin{pmatrix} {\rm e}^{{\rm i}\alpha/2} \\ {\rm e}^{-{\rm i}\alpha/2} \end{pmatrix}, \quad |\Psi_-\rangle = \begin{pmatrix} {\rm i}\,{\rm e}^{{\rm i}\alpha/2} \\ -{\rm i}\,{\rm e}^{-{\rm i}\alpha/2} \end{pmatrix}. \tag{13}$$

Rewriting the optomechanical interaction term $\hbar g a^{\dagger} a(b^{\dagger}+b)$ in the supermode picture,[130] we find that the effective coupling strength between the supermodes and the mechanical mode is

$$g_{\rm eff} = \frac{g\left(\Gamma+\sqrt{\Gamma^2-J^2}\right)}{2\sqrt{\Gamma^2-J^2}}, \tag{14}$$

with $\Gamma=(\kappa+\gamma)/2$. Clearly, near the phase transition point $J=\Gamma$, the effective single-photon optomechanical coupling can be greatly enhanced and becomes optimal at this point. This implies a drastic enhancement of sensitivity for nonlinear measurement of the mechanical motion. The sensitivity enhancement can be intuitively understood as: (i) on the one hand, the active cavity amplifies the backaction spectrum of the mechanical mode; (ii) on the other hand, the gain-loss balance in the $\mathcal{PT}$-symmetric system makes the background spectrum narrower. These two effects increase the measurement sensitivity.[216]

3.2. Squeezed-light-enhanced optomechanical coupling

The optomechanical interaction can be used to generate squeezed light. Interestingly, it has been proposed in Ref. [217] that the squeezed cavity mode can be used to enhance the optomechanical coupling strength. As schematically shown in Fig. 3, the optical cavity contains a nonlinear medium, degenerate optical-parametric-amplifier (OPA), which is pumped with an external laser with tunable amplitude and phase. Here, the nonlinear medium is used to squeeze the cavity modes by optical parametric process. The OPA could also be used to enhance optomechanical cooling,[218,219] control and manipulate the electromagnetically induced transparency,[220,221] or enhance the entanglement of optical or mechanical modes.[222,223] In Ref. [217], it was found that the noise of the squeezed cavity mode can be suppressed by introducing a broadband squeezed vacuum when its phase matches with that of the parametric amplification. Based on the enhanced coupling strength and suppressed quantum noise, it should be feasible to observe photon antibunching[224] or non-Gaussian state preparation,[225] using a weakly coupled cavity optomechanical system. Here, the squeezed optical field can be realized by a cavity-based degenerate parametric amplifier,[226–229] or dissipative interactions.[230–235]

Besides squeezed state enhanced optomechanical coupling, the single-photon optomechanical interaction can also be enhanced via a parametric driving field applied to the mechanical resonators. This scheme results in an exponential enhancement of the single-photon coupling constant g, and the enhancement can be controlled by the amplitude and detuning of the driving field.[236] It enables true quantum nonlinearity even when the single-photon coupling g is much smaller than the cavity-damping rate κ.

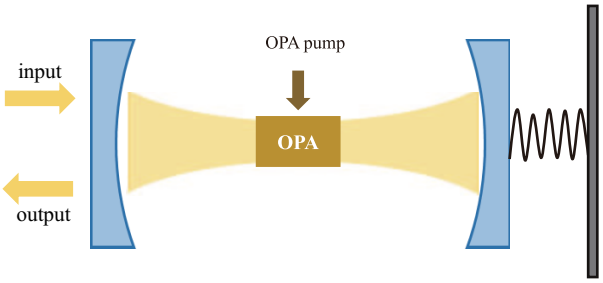


Fig. 3. (color online) Schematic structure of an optomechanical system that consists of a degenerate OPA (nonlinear crystal) inside the cavity. The nonlinear crystal is pumped by an additional laser beam to produce a squeezed optical field to enhance the single-photon optomechanical coupling strength.

3.3. Quantum-emitter mediated strong optomechanical coupling

The optomechanical coupling can also be enhanced by indirect coupling, e.g., mediated by two-level quantum emitters, as schematically shown in Fig. 4. Along this way, it has been proposed to enhance optomechanical coupling via the Josephson effect.[237] The proposal involves a tripartite system, consisting of a two-level artifical atom, a microwave cavity, and a micromechanical resonator.[238] The single-photon optomechanical coupling strength can be enhanced by a large factor. The enhancement factor can be obtained by a simple Josephson inductance picture or a Schrieffer–Wolff-type approach, where the effect is obtained as a systematic perturbation theory on the tripartite quantum system.[239] Besides enhancing the optomechanical coupling, the two-level quantum emitters, e.g., Cooper pair transistor,[240] are also possible to add mechanical and cavity dampings due to the hybridization of the different parts of the system. It can also enhance the sensitivity to detect the mechanical displacement.[241–244]

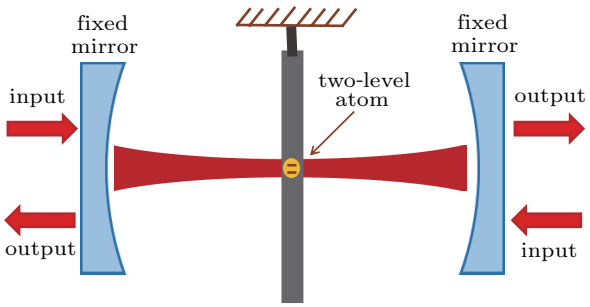


Fig. 4. (color online) Schematic diagram for the quantum-emitter-mediated optomechanical systems. A two-level quantum emitter (e.g., defect, quantum-dot, and superconducting qubit) is simultaneously coupled to the cavity field and the mechanical mode. The quantum emitter can induce an indirect and controllable optomechanical coupling.

Recently, superconducting quantum interference devices (SQUID) were explored for all-electrical realizations of analogs to optomechanical systems.[245] Two transmission-line resonators (resonator A, and B) are coupled to each other through the SQUID terminating resonator A.[246] The coupling mechanism is that the magnetic field in resonator B, threading the SQUID loop of resonator A, changes the

phase across the SQUID. This introduces an optomechanical-type interaction. Here, the effective optomechanical coupling strength is tunable, and depends on the properties, including the bias conditions of the SQUID and the detailed geometry of the coupling (e.g., inductive coupling or galvanic coupling). The device is a promising candidate for realizing the single-photon strong coupling, and could be used in microwave-photon-based quantum simulation.[247]

Very recently, ultrastrong coupling between the two-level systems and cavity fields has been realized in, for example, semiconducting and superconducting devices, especially towards the deep-strong coupling where the interaction strengths are comparable to the bare frequencies of the light and the matter.[248] In the deep-strong coupling regimes, the states of the whole system are dressed by virtual photons,[249–254] which are negligible in weak and strong coupling regimes. It has been proposed that such virtual photons can be further explored to enhance the single-photon optomechanical coupling strength. The system is now a hybrid device of a matter, cavity, and mechanical resonator, where a mechanical mode is coupled to a cavity-QED system. The matter represents a general two-level system, including superconducting qubit, quantum dot, and NV-center. The interaction between the cavity field and a matter degree of freedom (modeled as a two-level system) is described by the quantum Rabi model with anti-rotating wave term. A recent work[255] shows that the photons, dressing the ground state of the strongly coupled cavity-QED system, can induce single-photon optomechanical coupling strength through the virtual radiation-pressure effect. Moreover, a modulation of the optomechanical interaction is also introduced to observe variations similar to the Casimir force.[256–261] As a result, one can observe the amplified ground-state occupation, where the displacement can be resolved from thermal and vacuum fluctuations. This requires a sufficiently large optomechanical coupling. Such a device may also allow an effective quantum nondemolition measurement.

3.4. Enhancing optomechanical coupling by periodic arrays of mechanical resonators

Another promising approach to enhance single-photon optomechanical coupling is to exploit collective optomechanical interactions, where many mechanical resonators are embedded to a single optical cavity.[262] This approach is similar to that using an ensemble of cold atoms, instead of a single atom, to enhance the optical-matter coupling strength. As schematically shown in Fig. 5, the optomechanical coupling of a specific collective mechanical mode can be several orders of magnitude larger than that of the single mechanical mode case.

In Ref. [263], the authors showed in detail that the collective motion of a periodic array of identical scatterers, placed inside a cavity field, can couple very strongly to the optical field. In this configuration, the array is transmissive in contrast to the usual reflective optomechanics approach. Regardless of whether the scatterers are atoms or mobile dielectrics, the coupling strength under this configuration scales superlinearly ($\propto N^{3/2}$) with the number of scatterers and does not saturate as the reflectivity of the elements approaches unity. In principle, this allows optomechanical systems to reach strong single-photon optomechanical coupling, and does not require wavelength-scale confinement of the light field. Concomitantly, in this configuration, the resonator field couples to a specific collective mechanical mode supporting internal interactions between different mechanical modes. It would also open up avenues for achieving strong single-photon optomechanical coupling with massive resonators, realizing hybrid quantum interfaces, and exploiting collective long range interactions in arrays of atoms or mechanical oscillators.[263]

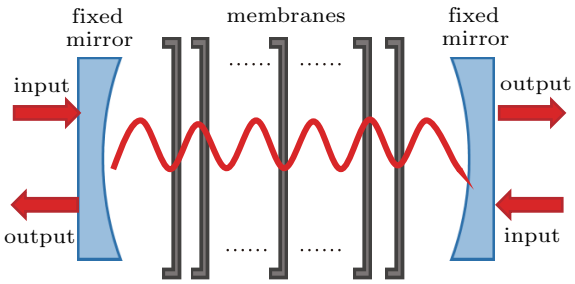


Fig. 5. (color online) Schematic diagram of optomechanical arrays. N identical and equidistant membranes are placed inside a Fabry–Pérot cavity. The distance between each two adjacent membranes is d. The cavity length L is assumed to be much larger than the length of the membranes arrays, i.e., $L \gg Nd$.

3.5. Other mechanisms to enhance the optomechanical coupling

Optomechanical crystals are also deeply explored to enhance the coupling between the optical field and the mechanical resonators at the nanoscale. In optomechanical crystals, imperfections induce extra loss of energy. This reduces the optomechanical coupling strength. In Ref. [264], the authors quantify the role of disorder in a paradigmatic one-dimensional optomechanical crystal with full phononic and photonic band gaps, and anti-intuitively find that such disorder can be exploited as a resource to enhance the optomechanical coupling beyond engineered structures. This study provides a new tool to enhance the single-photon optomechanical coupling strength.

For a conventional optomechanical system, where a mechanical membrane is inserted into an optical Fabry–Pérot cavity, the optomechanical coupling strength is proportional to the electric susceptibility of the membrane resonator. Ref. [265] shows a method to enhance the optomechanical coupling via the refractive medium, which results in a tunable susceptibility. In particular, a tunable ultra-large refractive index without absorption can be obtained by doping atoms or

spins into the membrane. If these atoms or spins are driven appropriately, then the giant susceptibility without additional absorption can greatly enhance the optomechanical coupling strength. Possible implementation of this scheme is proposed by using Er^{3+} dopants at low temperature, and Cr^{3+} in a Ruby membrane at room temperature. This scheme can also support a tunable and wide-range coupling strength.

In the microwave domain, it has been proposed to realize single-photon strong or ultrastrong optomechanical coupling by using a dynamical Casimir effect. References [266] and [267] describe a hybrid optomechanical scheme involving a SQUID. This structure has been proposed and deeply explored as a displacement detector,[268–271] but without the cavity mode. However, in Ref. [266], it was evaluated in the context of ultrastrong coupling or time-dependent external flux driving. By modulating an external flux applied to the SQUID loop, the variation of effective inductance of the SQUID modulates the frequency of the cavity mode nonadiabatically. This results in photon production from the quantum vacuum, and can be viewed as a nonlinear $\chi(2)$ susceptibility. By amplifying quantum vacuum fluctuations of the cavity mode and modulating its electrical length, an effective nonlinear medium can be achieved. Under the condition that the modulation frequency is much bigger than the mechanical frequency, the effective single-photon optomechanical coupling strength can be on the order of the normalized cavity frequency, i.e., the ultra-strong optomechanical coupling is obtained. Besides the SQUID, a superconducting strip at the tip of a cantilever, which is in the Meissner state, is also used to enhance the optomechanical strength in the microwave cavity electromechanical system. The position-dependent magnetic response of the superconducting strip leads to a strong magnetomechanical coupling to quantum circuits.[272] For hybrid cavity-electromechanical systems, strong optomechanical coupling or Kerr nonlinearities can be induced by the quantum-criticality.[273] In principle, the optomechanical coupling strength can also be enhanced by using optical coalescence,[274] weak measurement,[275] and two-mode interaction.[276–278]

4. Experimental progresses on engineering the optomechanical coupling strength

Benefiting from the development of the modern micro/nono-fabrication, one can design and fabricate the optical cavity and mechanical resonator with a very high Q-factor. The structure of the cavity optomechanical systems becomes much richer and the optomechanical coupling strength is more controllable. In this section, we review experimental progresses on engineering optomechanical coupling in different types of optomechanical systems, including Fabry–Pérot, whispering-gallery, photonic-crystal, and electromechanical systems. Engineering the optomechanical coupling strength by using novel material is also summarized here. To give an intuitive understanding of the importance of the optomechanical coupling strength, we review its application, for example, controllable photon or phonon transport with the improvement of the coupling strength.

4.1. Fabry–Pérot cavity optomechanical systems

The optomechanical interactions have been well studied in the typical Fabry–Pérot cavity structure, in which one mirror is fixed while the other one can move and works as the mechanical oscillator. In 1983, the optomechanics based on Fabry–Pérot cavity structure was proposed and realized,[279] where the frequency of the mechanical resonator is 1 Hz. The authors studied the typical hysteresis cycle of transmitted powers, also known as the bistable behavior induced by the radiation pressure. Due to the strong classical noise of laser and the weak radiation pressure, the experiment has not reached the quantum regime. The modern cavity optomechanical experiment began in the late 90s, based on the improvement of micro/nano fabrication technology. It uses the narrow linewidth laser and a high-quality-factor cavity to enhance the optical backaction. Besides the optical aspect, the mechanical resonators with high quality factor and frequency are also fabricated to reduce the Brownian noise. These advancements make it possible to do experiments approaching the standard quantum limit.[280–282]

To further enhance the mechanical frequency, a silicon doubly-clamped (1 mm×1 mm×60 mm) beam with a mirror coated upon its surface (working as a back mirror of a single-ended Fabry–Pérot cavity) was designed and fabricated.[283] The effective mass of the mechanical resonator is 190 μg and the mechanical frequency is 814 kHz with a spring constant 5×10^6 Nm^{-1}. The mechanical quality factor was measured to be 10^4 in a vacuum and at room temperature. The optical finesse is 3×10^4, with a cavity bandwidth 1.05 MHz. By red detuning the laser frequency from the cavity frequency, a rapid cooling of the mechanical resonator induced by intra-cavity radiation pressure was observed. The mechanical resonator was then cooled down to an effective temperature of 10 K. Oppositely, for the blue detuned pumping with respect to the cavity frequency, one can observe an efficient heating process for the mechanical oscillation, as well as a radiation-pressure-induced instability of the optical fields. Meanwhile, a cantilever, consisting of a doubly-clamped free-standing Bragg mirror (520 mm×120 mm×2.4 mm), was also fabricated[284] through ultraviolet exciter-laser ablation in combination with a dry-etching process. The reflectivity of the Bragg-mirror reaches 99.6% at the wave-length 1064 nm. The frequency

of the mechanical mode is 280 kHz with a quality factor 9000 and a natural width of 32 Hz. Then, with this device, a self-cooling of the mechanical resonator, induced by radiation pressure, was reported without any active feedback, and the mechanical resonator can be cooled from room temperature (300 K) down to 10 K. The quality factor of the mechanical resonator can also be further improved. As reported in Ref. [285], one tiny plane mirror (30 mm in diameter) was attached to a commercial atomic force microscope cantilever (450 μm×50 μm×2 μm) to reduce the mechanical decay and its effective mass. Such a mechanical resonator holds a fundamental frequency of 12.5 kHz and the quality factor reaches up to 1.37×10^5. With this optomechanical device, the micromechanical resonator was cooled down to 135±15 mK with an active optical feedback cooling. So far, the decay of optical cavity is much larger than the frequency of mechanical resonator. This sets an inherent limit to the optical radiation pressure cooling rate. To achieve ground-state cooling, on the one hand, we should improve the cooling rate by further decreasing the cavity loss rate and increasing the frequency of mechanical resonator. On the other hand, we can suppress the heating rate through red-sideband driving and resolved-sideband cooling scheme.

Towards this direction, an all-optical trap for a gram-scale mirror structure[286] and the self-cooling of the micromirror resonator in a cryogenic environment[287] are studied. Moreover, the processing technology of the micromirror was further developed to obtain a high-quality-factor mechanical resonator with exceptionally low intrinsic absorption for the optical modes.[288,289] The frequency of fundamental mechanical modes was improved to approach MHz. The mechanical quality factor reaches up to 3×10^4 which was measured at 5.3 K. The micromirror comprises 36 alternating layers of Ta_2O_5 and SiO_2 with an overall nominal reflectivity of 99.991% at 1064 nm and an optical cavity finesse 3900.

With these improvements, opto-mechanical normal mode splitting was observed. This provides unambiguous evidence for achieving strong coupling between a micromechanical resonator and an optical cavity field.[88] Based on the linearized strong optomechanical coupling strength, the mechanical quantum state tomography was demonstrated using short optical pulses.[172,290] Despite that the mechanical resonator was initialized in a thermal state, this structure allows us to observe the quantum features of a mechanical oscillator. Further, the preparation and reconstruction of mechanical quantum states were experimentally studied.[291] In 2015, Kalman filters for optimal state estimation of cavity optomechanical systems were also realized.[292] This laid a fundamental basis for preparation, measurement, and real-time control of macroscopic quantum states.

Besides the experimental setup that the mirror acts as the mechanical resonator to construct the optomechanical system, the optomechanical system can also be formed by placing a mechanical membranae inside the Fabry–Pérot cavity. It means that the mechanical resonator has been separated from the optical cavity, this leads to flexible and individual control of each component. The optomechanics was demonstrated in a cavity modulated by an SiN membrane (1 mm×1 mm×50 nm) on a silicon chip inside the cavity.[293] The lowest resonance frequency of such membranae is 134 kHz, with an effective mass 40 ng. These parameters correspond to the mechanical quality factor up to 1.1×10^6. In such a setup, the mechanical mode was cooled down to 6.82 mK with a red-detuned laser. The membranae-in-the-middle structure allows for direct observation of energy eigenstates and quantum jumps of the mechanical modes. Such structure was also further developed to study the quadratic optomechanical coupling,[294] which has been increased three orders of magnitude compared to that of previous devices in mirror-in-end structure.[293] It has shown that the tunable coupling between mechanical motion and optical field can be widely used to control the transport of the optical fields. In particular, the strong nonlinear quadratic coupling can be used to observe the membrane energy quantization without further engineering the nonlinearities of the mechanical modes.

To further reduce the noise of the laser, a passive filter cavity was used to remove classical laser noise in a cryogenic optomechanical system. The future requirements for laser cooling of the mechanical element close to its ground state were discussed.[295] After that, reference [296] reported measurements of the motion sidebands, produced by a mechanical oscillator, which is cooled close to its quantum ground state with the resolved-sideband cooling scheme. The mechanical mode was fabricated with an effective mass 43 ng, a resonant frequency 705.2 kHz, and a mechanical linewidth 0.1 Hz, while the optical mode has a linewidth of 165 kHz with an optical finesse 4×10^4. The mechanical mode was then cooled down using the resolved-sideband cooling scheme, and the final mean phonon number in steady state was 0.84±0.22 (corresponding to a mode temperature of about 28 ± 7 μK). Recently, a micromechanical membrane resonator was further cooled down to the quantum backaction limit with final phonon occupation[272] of 0.20 ± 0.02.

Another advantage of the Fabry–Pérot cavity optomechanical system is its powerful ability to construct the hybrid optomechanical devices with other quantum systems, e.g., cold atomic ensembles. A hybrid optomechanical system was realized by coupling the ultracold atoms to a micromechanical membrane.[298] These atoms were first trapped in an optical lattice, driven by a laser retroreflection from the mem-

brane surface. The coupling between membrane vibrations and atomic motion was induced by the lattice laser. The dissipative rate of the membrane could be engineered by coupling to the laser-cooled atoms. With atomic hybridization, the cooling of the membrane vibrations from room temperature to 650±230 mK has been reported.[299] By coupling the membrane vibrations to the atomic motion, mature atomic laser cooling technology makes it possible to relax the constraints of pure cavity optomechanical or feedback cooling techniques.

These investigations indicate that the Fabry–Pérot cavity optomechanical system becomes more and more mature for controlling both the optical field transport and mechanical oscillation. The optomechanically induced transparency was demonstrated in a cavity optomechanics formed by a semitransparent membrane in the middle of a Fabry–Pérot cavity.[300] A weak probe field was completely transmitted when the red detuning of the pump field equals to the frequency of the mechanical resonator. The COMIT can be used to delay the transport of the probe light. The similar but totally different phenomenon is electromagnetically induced amplification. It has also been observed with a blue sideband detuning pumping. A topological energy transfer in an optomechanical system was proposed and realized in the Fabry–Pérot cavity optomechanical system to control the transport of phonons.[301] The adiabatic topological operation allows for non-reciprocal energy transfer between two different mechanical modes.

In order to overcome the extra dissipation induced by suspended coating mechanical oscillator, mechanical oscillators with high-quality-factor were further explored. For example, a monolithic high-reflectivity cavity mirror from a single silicon crystal, avoiding the coating thermal noise problem, was designed and fabricated.[302] Additionally, to obtain a high-frequency mechanical resonator, a micropillar geometric shape was designed.[303] This structure can support mechanical mode with high-quality-factor (up to 5×10^6) and a low effective mass 25 μg. The integrated photonic crystal and Si-waveguide optomechanical system[304–306] was developed and the mechanical frequency has further been increased up to 10 MHz. To reduce the affects of the thermal noise, the on-chip membranes were designed,[307–310] with remarkably low dissipation rates of 1.4 mHz. This provides a unique platform for the observation of macroscopic quantum behavior at room temperature.

4.2. Whispering–Gallery–Mode cavity optomechanical systems

The Whispering–Gallery–Mode cavity takes advantage of the long lifetime of photons and small mode volume. Due to total reflection, the light transports along the circumferential direction of the toroid, and the vector of its momentum becomes opposite. This results in a radiation pressure on the cavity wall. The Whispering–Gallery–Mode cavity optomechanical devices provide a powerful platform for the experimental study of dynamical optomechanical interaction, which could be used to manipulate the transport of the optical field and the mechanical motion. Here we review the improvement of optomechanical interaction by engineering its geometric structure and the fabrication process.

In Ref. [311], the excitation of the mechanical mode in the Whispering–Gallery–Mode cavity was observed. The radiation pressure was the excitation source of the observed mechanical oscillations. The reported effective mass of the mechanical resonator in this device is about 50 ng. The frequency and decay rate are 4.4 MHz and 1.25 kHz, respectively. The quality factor of the mechanical resonator reaches 3500. The decay rate of the optical field in a microtoroid is about 10 MHz. It has been proposed that the resolved sideband cooling is a promising way to cool the mechanical motion to the ground state. Such a proposal requires that the frequency of the mechanical mode should be larger than the decay rate of the optical cavity to suppress the heating rate and obtain a net cooling rate. Reference [312] proposed a spoke-anchored toroidal resonator to enhance the mechanical frequency and reduce the clamping losses of the mechanical resonator. The effective massive of the mechanical resonator is also reduced due to its spoke structure. This results in a low-pump threshold excitation of the mechanical motion. Both of these improvements in turn result in a higher optomechanical coupling strength compared to that of the conventional microtoroid cavity. Devices, fabricated in the spoke-anchor manner with radius 515 mm in this work, exhibits optomechanical coupling rates as high as 3.4 kHz for a mechanical resonance frequency of 78 MHz, an optical decay less than 10 MHz, and a critically resolved-sideband factor for ratio 11 between the mechanical frequency and the cavity decay rate. Although the single-photon optomechanical coupling has been improved through spoke-anchored design, it is still much smaller than the decay rate of the cavity, corresponding to the weak coupling regime. An externally strong pump is tailored to obtain a strong and linearized optomechanical coupling. As a result, a quantum-coherent coupling between the optical photons and the mechanical motion has been observed, at the same time, the mechanical oscillator was cooled to an average occupation of 1.7 motional quanta.

To further improve the coupling strength and mechanical quality factor, the geometric dimensions can be optimized by reducing the thickness of both the spokes and the pillars.[313] Such a device consists of a toroidal boundary, supported by four spokes. The outer torus is connected to the silicon chip

via silica bridges. This design can decouple the radial motion from the clamping area in the centre of the disk, resulting in an ultralow dissipation rate. The measured mechanical quality factor is up to 8×10^4 with mechanical frequency larger than 30 MHz. Such structure also allows an independent control over both the mechanical and the optical modes on a single onchip device.

Another method to enhance the optomechanical coupling is to separate optical cavity from mechanical resonator. This scheme presents maximum flexibility to engineer the parameters of the optical field and mechanical resonator simultaneously. As reported in Ref. [48] a doubly clamped, high-stress Si_3N_4 nanomechanical beam is coupled to a silica microdisk resonator via evanescent near-field. The bevel for the edge of the disk was optimized to minimize the decay rate of the cavity field through finite-element simulation of the electromagnetic field distribution of the fundamental optical mode, confined in the microdisk resonator. The Si_3N_4 material holds a high elastic modulus and may be the best material to make mechanical resonator with high quality factor. The beam, used in this work, has dimensions of 90 mm$\times$700 nm$\times$100 nm, and the microdisk has a diameter of 76 mm. Under this structure, the optomechanical coupling strength was improved to $\partial\omega/\partial x = 2.9$ MHz·nm^{-1}, which in turn enhances the displacement sensitivity and also makes it possible to observe the motion of cantilevers below the diffraction limit.

Besides the evanescent near-field optomechanical coupling, the optical gradient force was also explored to enhance the optomechanical coupling strength.[38,314,315] The double-disk was separated by a nanoscale gap region on a silicon chip for cavity optomechanics. The structure features a gradient-force-induced optomechanical coupling, which enables improvement of the optomechanical coupling strength. As reported in Ref. [154] two double-disk optomechanical cavities are coupled closely enough in space to induce energy transfer between these two double-disk optomechanical systems. As a result, the frequency synchronization of two mechanical oscillators was observed under distance by a few hundred nanometers. Here, the mechanical oscillators are not directly coupled. Instead, the optical cavity fields work as the bus to connect these two resonators. These results pave a path toward reconfigurable synchronized oscillator networks.[163,316]

Combining the spoke structure and optical gradient force in a double disk,[317] a novel optomechanical system was then proposed and the optomechanical coupling strength is further improved. In Ref. [318], a resonant cavity sensitive to the optical gradient forces, was designed. In this design, two vertically stacked ring cavities are held by a very thin pedestal. This structure results in a high sensitivity even to small changes in the distance between the rings. The spokes are designed to enhance the mechanical rubbing of the cavity, and to increase the sensitivity to the optical forces between the rings. The gap between the top and the bottom resonator is about 640 nm. The Si_3N_4 material is chosen to introduce a relatively small refractive index. This makes strong optomechanical coupling possible for relatively large gaps between the top and the bottom resonators. As a result, the optomechanical coupling strength is greatly improved and transverse mode profiles are changed into symmetric and antisymmetric combinations which lead to two supermodes with distinct resonant frequencies.

With the increase of the optomechanical coupling strength, the Brillouin-scatter effect becomes much more important, and is widely explored in micro bottles[319] and microspheres.[23] Required by the momentum and energy conservation, Brillouin-scattering induced transparency was explored to generate ultralow-power and footprint slow-light. It also enables non-reciprocal light transport. In Ref. [320], a multi-channel cavity optomechanical system was designed and fabricated with two separated wave guides. This structure allows the control of non-linearity of optical force, all-optical signal amplification and wavelength reuse. A bovine-eye like cavity system was also reported with a high mechanical quality factor and gigahertz frequency.[321] By using diamond materials, the system can be hybridized with spins and further explored to study many-body interactions.[322]

4.3. Photonic crystal cavity optomechanical systems

In this section we will review recent developments for improving optomechanical interaction in photonic crystal systems. Besides the optical cavities, the mechanical resonators can also be fabricated in the nano-structure film through periodic patterning.[323] This results in a localized photon-phonon interaction in a single device. Three main aspects motivate the developments of optomechanical crystal. (i) The periodic nanostructures support a high quality mechanical resonator with small mass. (ii) The localized optical and mechanical mode could induce a strong optomechanical coupling. The basic mechanism is similar to that using collective mechanical mode to enhance the optomechanical strength. (iii) Flexible photonic crystal drilling provides more freedom for developing complex optomechanical structure. In addition to the basic study of two-body linear optomechanical interaction, e.g., state conversion and storage, the optomechanical crystal would also allow the observation and study of non-traditional collective dynamics.

In Ref. [324], the zipper cavity optomechanical crystal was designed and fabricated. The mechanical resonator has a mass of pg order of magnitude. Compared to the Fabry–Pérot cavity and Whispering–Gallery–Mode cavity, the mechanical mass has been greatly reduced. The optomechanical

coupling is exponentially proportional to the slot gap between the beams. Under the zipper-like structure, the in-plane differential motion of the nanobeams is strongly coupled to the optical cavity field, whereas common motion is nearly decoupled. Especially, the beam widths are on the order of the wavelength of light, resulting in an optomechanical coupling strength several orders of magnitude larger than that obtained in the Fabry–Pérot cavity or Whispering–Gallery–Mode structures. In addition, a flexible design of the geometry shape can greatly vary the mechanical stiffness and frequency, in turn, resulting in a stronger optomechanical coupling strength. A silicon nitride (Si_3N_4) film, having a thickness of 400 nm, was first deposited on a silicon wafer using a low pressure chemical vapor deposition method. A zipper-shaped pattern was then generated by the electron beam lithography. The patterned zipper cavity consists of beams of length 25 μm∼ 40 μm, and width 0.6 μm∼ 1.4 μm, with a slot gap of 60 nm∼ 250 nm. A C_4F_8-SF_6-based plasma etch was used to transfer the pattern into the Si_3N_4 substrate. A wet chemical etch of KOH was used to release the patterned beams. In this device, the optical spring effect, including optical force, induces mechanical frequency shift and optical damping or gain.

With the development of the zipper cavity, an accordion-like optomechanical crystal was fabricated by patterning holes in a quasi-one-dimensional nanobeam.[325] Such a structure can support much more abundant optical and mechanical modes with high quality factor. The mechanical frequency is improved to gigahertz. The experiment demonstrated an optomechanical coupling between 200-THz photons and 20-GHz phonons in a planar optomechanical crystal. The breathing mode, accordion mode, and Pinch mode were calculated via finite element methods. The mechanical spectroscopy of this device was detected through a taper waveguide coupled to the optical mode. The basic parameters for different mechanical modes were obtained and had a good correspondence to the results obtained from simulations. The frequency for the pinch mode is 0.8 GHz, with quality factor less than 10^3. The frequency for the accordion mode is 1.4 GHz with quality factor about 10^3. The breathing has a frequency 2.25 GHz and the quality factor is less than 1.3×10^3. These structures of optomechanical crystals provide sensitive optical measurements of mechanical vibrations, and simultaneously induce strong nonlinear interactions of photons in a large and technologically relevant range of frequencies.

To further increase the optomechanical coupling in photonic crystal devices, the slot-mode-coupled optomechanical system was designed and fabricated. In Ref. [326], the quality factor of the optical mode was improved and became larger than 10^6. The optical field is evanescently coupled to a localized mechanical mode with gigahertz. The device was still designed in a nanobeam structure, whereas the pore sizes were changed. The optical and mechanical modes can be free of mutual interferences by using separated nanobeams to provide the optical cavity and mechanical resonator, independently. Such structure supports typical mechanical mode with frequency 1.38 GHz and its effective mass is only 1.8 pg. The size optimization in turn enables a large zero-point optomechanical coupling strength, for example, the single-photon optomechanical coupling strength is larger than 300 kHz in an Si_3N_4 nanobeam at 980 nm and about 900 kHz in an Si nanobeam at 1550 nm. The large coupling strengths to GHz mechanical resonators was achieved in the Si_3N_4 nanobeam. This paves the way for wide-band optical frequency conversion. The Si_3N_4 material has a broad optical transparency window and allows it to operate throughout the visible and near-infrared. For example, a frequency conversion between 1300 nm and 980 nm, using two optical nanobeam cavities coupled either side to the breathing mode of a mechanical nanobeam, has attracted a great deal of attention.

Recently, two-dimensional phononic-photonic band gap optomechanical crystal, instead of one-dimensional periodic mechanical structures, has been proposed to expand the mechanical frequency to microwave *X*-band and to introduce a strong optomechanical coupling. These two-dimensional-planar structures can support photonic and phononic band gaps simultaneously.[327] Another kind of two-dimensional device demonstrated a planar snowflake structure.[328] The snowflake lattice was used to tailor the properties for both the optical fields and the acoustic waves. The strong optomechanical coupling, that exists between localized optical and mechanical modes, was characterized through two-tone optical spectroscopy. The mechanical frequency is about 9.3 GHz, and the single-photon optomechanical coupling strength is evaluated as 220 kHz. The snowflake 2D light optomechanical structure can also be expanded to realize multibody photon and acoustic interaction. It could allow us to capture and store optical pulses, or filter and route optical signals through microwave photons. Benefiting from the snowflake 2D structure, the thermal conductivity of the mechanical vibrator can be greatly reduced. This platform allows the studies of the macroscopic quantum physics in future.

The designed 2D-snowflake structure can also effectively reduce the decay rate of the mechanical resonator. Thus, it has been used to optimize the optomechanical crystal cavity with an acoustic radiation shield.[329] This results in a nanobeam with an experimentally realized intrinsic mechanical frequency at 5.1 GHz, and a mechanical Q-factor of 6.8×10^5 measured at 10 K. The single-photon optomechanical coupling strength has also been improved to 1.1 MHz. Besides the conventional Si and Si_3N_4 materials, the diamond

material has also been used to engineer the optomechanical interaction.[330] The extremely high stability and hardness of the diamond provide a powerful platform for measuring the signal under extreme conditions. On the other hand, the NV center has been widely explored for solid-state quantum information processing. So, the diamond optomechanical crystal could be further explored to study the hybrid optomechanical system with spins.

4.4. Electromechanical system

Microwave cavity electromechanics is a part of nano-electromechanics and micro-electromechanics; it mainly studies the interaction between electric field and mechanical motion in the microwave domain. Microwave cavity electromechanical systems are effective platforms to explore and interpret macroscopic quantum behavior using mechanical oscillators. Cavity electromechanics was originated from circuit quantum electrodynamics (cQED)[248] and developed for observing the quantum effects in nano-elctromechanical systems and exploring gravitational waves. At the same time, the quantum characters of microwave fields have been experimentally demonstrated using cQED. Such as, Josephson junctions are used to create artificial atoms (qubits) and design superconducting resonators with tunable frequencies. The coherent coupling between single microwave photon and qubit has already been experimentally realized.[248] This leads to a general considerations of achieving strong interaction between microwave photons and mechanical motion, where the quantum characters of mechanical motion and microwave radiation pressure could be observed. In practice, a superconducting circuit with a mechanical element is typically associated with the Hamiltonian that describes a Fabry–Pérot cavity optomechanical system. Mechanical motion changes the resonant frequency of the superconducting circuit and in turn introduces the dispersion coupling between microwave photon and mechanical resonator.

The microwave cavity-electromechanical system has many attractive features. For example, the superconducting circuit is compatible with current semiconductor technology. It facilitates the integrated circuit design and production. The circuit resonator can be designed flexibly and the structures of the mechanical oscillators (e.g., nanobeam and tympanic-membrane) are diverse. These features allow the superconducting microwave circuit to generate specific optomechanical interactions, for example, the qubit mediated nonlinear and strong coupling. The electromechanical systems are also good platforms to study multimodes optomechanical interactions. The localization of interacting photons, phonons, or photon-phonon polaritons in mulitmodes optomechanical systems also recently emerges. With photon and phonons, exotic phenomena, thought to exist only in strongly interacting electronic systems (such as Mott transitions, Fractional Hall effect, spin-charge separation, interacting relativistic theories, and topological physics) can be reproduced and understood in more detail. The quantum simulator with photon-phonon polaritons is also a relatively new and fantastic research subject. Since the microwave cavity electromechanical system can be compatible with cryogenic technology, the experiment can be carried out at low temperatures (usually less than 1 K). This greatly eliminates the impact of random thermal fluctuations upon mechanical quantum states. Similarly, the microwave cavity, formed by the lithographic superconducting film, is very stable compared to the optical microcavity, so the frequency locking and stabilization techniques can also be avoided.

Here we introduce several typical achievements in cavity-electromechanical systems, e.g., preparation and transfer of quantum states of microwave fields or mechanical modes. In Ref. [331], a capacitive elbow coupler was used to couple the microwave photons and measure the nanomechanical motion. The microwave cavity was formed by a 5-μm wide central conductor, 10 μm off the ground. The resonant frequency of the microwave mode is 5 GHz, with a decay rate of 490 kHz. The quality factor is 10^4. The cantilever beam mechanical frequency is 2.3 MHz, and the quality factor is 1.2×10^5 at 17 mK. Under such structure, the single-photon coupling strength was measured and given as 1.16 kHz/nm.

To improve the electromechanical coupling strength, in Ref. [332], the high stress SiN mechanical resonator was coated with Al. The nano-mechanical oscillator interacted with the superconducting microwave resonator through the capacitive coupling. The high stress SiN-nano-mechanical oscillator has a very low dissipation rate, and its quality factor can reach 10^6. The mechanical resonator has a resonant frequency at 5.57 MHz and a decay rate of 25 Hz. The resonant frequency of the superconducting microwave cavity is 5.01 GHz with the decay rate 494 kHz. The single-photon coupling strength has been increased to 7.5 kHz/nm. The quantum non-destructive measurement of the nanomechanical oscillator was then experimentally observed. With such electromechanical structure, thermomechanical vibrations at 25 mK were measured and a number of about 20 phonons were obtained in the equilibrium.[333] The frequency of the nanometer mechanical resonator is as high as 67 MHz with the quality factor about 2.7×10^5. In this work, the single-photon coupling strength was increased to 1 MHz/nm.

In order to further improve the coupling strength of the optical field and mechanical resonator, the tympanic capacitive mechanical oscillator was designed.[334] The single-photon coupling intensity 100 MHz/nm is two orders higher than that

obtained in Ref. [294]. The intrinsic frequency of the optical cavity is 7.5 GHz with a decay rate 170 kHz. The frequency of the tympanic mechanical vibrator is 10.69 MHz with the decay rate of 30 Hz and a quality factor of 3.7×10^5. In the experiment, the pump light was used for increasing optomechanical coupling to the strong coupling regime, in which the well-known normal-mode splitting phenomenon was observed. The electromagnetically induced transparency of the microwave field and the cooling of the mechanical resonator under the weak coupling condition were also demonstrated.

To further reduce the mass and improve the mechanical frequency, a superconducting cavity mechanical system in the silicon insulator platform[335] was designed and fabricated. The mechanical quality factor was also increased to 1.7×10^7. The quantum properties of silicon nitride nanomembranes were studied in Ref. [336]. With such kind of devices, electromagnetically induced absorption and transparency were observed in experiment, and the mechanical resonator was cooled down to its ground state with an average phonon occupancy of 0.32. Using a coherent feedback network,[337] the coupling between the microwave photons and mechanical resonators was further increased, and the microwave decay rate could be modulated by 10^4 times greater than the mechanical decay rate.

In general, the cavity-electromechanical system plays an important role in the control of the microwave signal transport, mechanical oscillator cooling, macroscopic quantum state preparation, etc. The coupling of the microwave cavity electromechanics with the optical cavity will further extend the application of the system to quantum information processing, for example, coherent quantum state transfer. High compatibility with low-temperature environments also makes it easy to integrate with the superconducting quantum circuits.[248] This supports a powerful platform to construct the hybrid quantum system.

5. Summary of single-photon coupling strength and future perspectives

In Table 1, we have summarized the single-photon optomechanical coupling parameters used for current experiments of optomechanical systems. It seems that the BEC-cavity optomechanical system has achieved the single-photon strong coupling.[126] The toroidal microcavities always hold high-quality-factor cavity and mechanical modes.[312] It shows great possibility to achieve the single-photon strong coupling by further reducing the optical mode volume and the effective mass of the mechanical resonator in the toroidal microcavity. Another promising platform to achieve this goal is the optomechanical crystal. By engineering the two-dimensional phononic-photonic band gap, the optomechanical coupling strength can be further improved.[327] The superconducting electromechanical systems have also achieved a great deal of attention. The compatibility with superconducting circuits[248] and the dilution refrigeration equipment makes it a powerful platform to study the macroscopic quantum effects. Very recently, the squeezed light generated by a Josephson parametric amplifier was used to enhance the optomechanical coupling strength and the radiation pressure.[338] With the increased optomechanical coupling strength, even low-frequency mechanical oscillators can in principle be cooled arbitrarily close to the motional ground state.[339,340] It can be further developed to suppress the Stokes scattering and realize the sideband cooling beyond the quantum backaction limit.[341]

Table 1. Summary of the parameters for current optomechanical experiments in microwave and optical domains. In the table, $\omega_c/2\pi$ and $\gamma_c/2\pi$ are the frequency and the decay rate of the cavity, the parameters $\omega_m/2\pi$ and $\gamma_m/2\pi$ are the frequency and the decay rate of the mechanical resonator, and g is the single-photon optomechanical coupling strength.

System	$(\omega_c/2\pi)$/Hz	$(\gamma_c/2\pi)$/Hz	$(\omega_m/2\pi)$/Hz	$(\gamma_m/2\pi)$/Hz	$(g/2\pi)$/Hz
Brillouin microcavity[17]	192 T	3.5 M	42.3 M	4 k	0.02
BEC[126]	385 T	1.3 M	15.1 k	10	0.39 M
FP cavity[289]	282 T	215 k	947 k	140	2.7
Membrane[293]	282 T	0.32 M	134 k	0.12	2.68
Toroidal cavity[312]	385 T	7.1 M	78 M	10 k	3.4 k
Double-wheel microcavity[317]	190 T	10 G	8.05 M	2.01 M	732 k
Optomechanical crystal[323]	195 T	500 M	3.68 G	35 k	910 k
Zipper cavity[324]	194 T	6 G	7.9 M	98.75 k	599 k
2D phononic crystal[327]	195 T	2.1 G	9.3 G	250 k	220 k
Electromechanical[334]	7.47 G	170 k	10.69 M	30	226
Graphene[342]	5.9 G	242 k	36.2 M	227.6	0.83
Magnon[343]	7.86 G	1.7 M	11.42 M	150	9.9 m
Plasmonic molecule[344]	330 T	33 T	30 T	60 M	(10–100) G
Levitate particle[345]	281 T	180 k	165 k	7.2 k	1.2
Superfluid[346]	194.5 T	46 M	317.5 M	5.3 k	3 k

Besides conventional mechanical resonators, two dimensional materials,[342] ferromagnetic magnons,[343] plasmonic molecules,[344] and levitate particles[345] were also extensively explored to construct novel optomechanical systems. The superfluid optomechanical systems, consisting of a miniature optical cavity filled with superfluid helium, support strong optomechanical coupling, which is close to serval Kilohertz.[346,347] However, the decay rates of the optical modes are enhanced when the cavity is soaked into the superfluid helium,[348,349] which is harmful for achieving the strong single-photon optomechanical coupling. To overcome this problem, the superfluid helium resonator was coupled into the microwave cavity[350,351] with very low loss, instead of the optical ones. The acoustic motion of superfluid He is parametrically coupled to the superconducting microwave resonator, and thus a gram-scale and sideband-resolved optomechanical system is formed.[352] In the microwave domain, the superfluid He resonator offers extremely low losses with quality factors as high as 1.4×10^7.[353] Acoustic quality factor approaches 10^{11} and the strong single-photon optomechanical coupling may be possible when the sample temperature is below 10 mK.[354,355]

By engineering an optomechanical structure and using novel material, great advances have been achieved on enhancing the optomechanical coupling strength for different types of optomechanical systems and there is a great possibility to realize strong single-photon coupling in future. These advances will enable new avenues to understand cavity optomechanics and to detect gravitational waves in small scale.[356]

6. Conclusion

The rapid progress in cavity optomechanics has been made in recent years with great achievements, including ground-state cooling of the mechanical resonator, optomechanical induced transparency, squeezed optical field, coherent state transfer, and photon-phonon entanglement. Most of the applications reported now are mainly based on the linearized optomechanical coupling, which is always induced by a strong control field. The intrinsic nonlinearity of optomechanical interaction has recently attracted a great deal of attention, especially at the single-photon level. Theoretical studies reveal a number of important applications for the quantum information process, for example, non-classical states preparation, single-photon source, phonon number transition, quantum state reconstruction, and multiphonon process, in the strong single-photon optomechanical coupling regime, where the coupling strength is comparable to the mechanical frequency, and at least to be larger than the decay rates of both the cavity field and the mechanical mode. In experiment, most of the optomechanical platforms hold a weak optomechanical coupling strength, except for the BEC-cavity optomechanical system. Thus, engineering optomechanical interaction towards strong coupling is a promising and urgent project.

In principle, two research directions should be further explored to realize this goal. One is to enhance the single-photon optomechanical strength. Along this direction, many talent mechanisms have been proposed and shown the great enhancement of the optomechanical coupling strength. Most of these methods show the possibility to be experimentally realized in the near future. Another direction to achieve single-photon strong coupling is to engineer the device structure and materials. Great efforts have been made to optimize the device structure (e.g., spoke, double disk, snowflake, and accordion-like patterns) in conventional Fabry–Pérot, Whispering–Gallery–Mode, Photonic-crystal, and LC-resonator cavity optomechanical systems. New materials include plasmon nanomechanics, superfluid helium films, molecular vibration, monolayer or multilayer graphene, carbon nanotube, optically levitated nanosphere, NV-center, and ferromagnetic magnons. Benefiting from optimizations of the structure and material parameters, the single optomechanical coupling strength for both the contentional and novel optomechanical systems has been greatly improved and shown great potential towards the strong regime.

Although realization of the strong single-photon optomechanical coupling in experiments still challenges current technology, important applications with the improvements of optomechanical coupling strength have extensively been explored, e.g., optomechanical nonlinearity induced optical chaos, mechanical synchronization, slowing light with high-order sidebands, which are summarized in the corresponding sections. We hope the works reviewed in this paper can further motivate more great ideas and experimental designs to achieve strong single-photon optomechanical coupling, which plays a key role in applications of quantum communication, sensing, and computing.

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