Cavity optomechanics with directionally squeezed light

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It is well understood that the Heisenberg uncertainty principle imposes a fundamental limit on the precision of quantum measurements. One way to get around this difficulty is to exploit quantum states that minimize the uncertainty on the observable of interest, increasing in the process the uncertainty on the conjugate observable. Squeezed states of the electromagnetic field, first demonstrated by Slusher and coworkers in a four-wave mixing experiment [1], permit to achieve this goal and to beat the standard quantum limit of optical amplitude and phase measurements. They have found applications in a number of optical detection schemes, and most spectacularly perhaps their implementation has resulted in significant noise reduction in interferometric phase measurements as performed in the LIGO/VIRGO gravitational wave antennas [2].

In addition to their central role in precision interferometry, squeezed states of light also find applications in radiometry, quantum information science, atomic clocks development, quantum imaging, and more. And in an intriguing recent application [3], optical squeezing was exploited to induce an optical nonreciprocity in a system of two coupled whispering gallery mode micro-ring resonators and two waveguides. When driving one of the resonators unidirectionally with a coherent field, a $\chi^{(2)}$ optical nonlinearity can be exploited to squeeze the state of a counter-clockwise rotating resonator mode, resulting in a chiral optical interaction between the two resonators and optical nonreciprocity. Nonreciprocity is a fundamental property of networks. It is an essential element of quantum gates and quantum networks and is also crucial for on-chip signal processing, routing, and isolation. As such optical nonreciprocity find applications across a number of fields including telecommunications, photonics, quantum information processing, and sensing.

Many of the ideas and techniques pioneered in quantum optics are now being applied and further developed in the exploding field of cavity optomechanics [4], in particular with the development of hybrid systems [5] that combine the advantages of quantized optical and phononic fields. Implementing directional quantum squeezing capabilities such as successfully exploited in Ref. [3] in such these systems permits to merge the benefits of nonreciprocal physics and COM represents therefore an extremely promising area of investigation.

This is beautifully illustrated in this issue of SCPMA, where Lu et al. [6] report on an elegant scheme to realize a nonreciprocal phonon laser by exploiting the properties of directional optical squeezing in a hybrid COM system comprised of an optomechanical resonator coupled to a nonlinear optical resonator driven by a strong optical field. They find that this results in an asymmetric coupling and detuning of the two resonators and in a significant modification of the mechanical gain and power threshold, and the generation of in nonreciprocal phonon lasing. The scheme, requiring only two-mode matching in one resonator, is free of any spinning device, and has the potential to be realized under current experimental conditions. Possible applications of this system include nonreciprocal force sensing, as well as chiral acoustic information processing or networking. Furthermore, these results open the way to the use of directional squeezing in hybrid COM devices [7] crucial quantum resources to a large number of emerging quantum technologies ranging from quantum information processing to quantum sensing, including nonreciprocal photon and phonon blockade, nonreciprocal macroscopic entanglement, and backscattering-immune force sensing.

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