SILICON NITRIDE CAVITY OPTOMECHANICAL TRANSDUCERS

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ABSTRACT

Planar fabrication technology has enabled the demonstration of on-chip systems in which interacting nanophotonic and nanomechanical resonators are directly integrated within a common platform. Such devices can be used for a variety of purposes in sensing, precision measurement, and signal transduction. Here, we review different nanocavity optomechanical systems that we are developing in thin film, stoichiometric Si_3N_4, in which mechanical modes with frequencies ranging from a few MHz to a few GHz are coupled to the optical modes of structures such as microdisk and photonic crystal cavities.

INTRODUCTION

Cavity optomechanical systems [1,2] involve the coupling of mechanical motion with the electromagnetic field inside an optical cavity. Our focus is on dispersively coupled systems in which mechanical motion results in a change in the resonance wavelength of an optical cavity mode. This fluctuating resonance wavelength, and hence the mechanical motion, can be easily read out by tuning a laser to the shoulder of the cavity mode resonance (Fig. 1(a)), or by measuring the phase on resonance with the cavity mode. The first class of device we describe in the next section is focused on sensitive optical readout of mechanical motion.

The change in the intracavity field induced by mechanical motion can feed back on the mechanical system when radiation pressure forces are appreciable. This feedback can lead to phenomena such as optically-induced stiffening of the mechanical mode (the optical spring effect) and cooling or excitation of the mechanical mode. On the other hand, this regime also enables observation of strong effects of the mechanical mode on the system's optical response. In particular, systems operating in the sideband-resolved regime (Fig. 1(b)), in which the optical cavity linewidth is less than the mechanical mode frequency, have been used to demonstrate effects such as electromagnetically induced transparency mediated by a mechanical mode [3,4] and wavelength conversion [5,6,7].

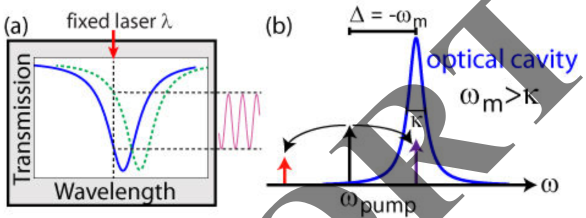

Figure 1. (a) Optomechanical readout. A fixed wavelength laser is intensity modulated when sent through an optical cavity whose resonant frequency is coupled to mechanical motion. (b) Sideband-resolved cavity optomechanics, where the cavity linewidth κ is smaller than the mechanical frequency ω_m. The cavity preferentially selects for one sideband produced when a pump laser drives the mechanical resonator.

Here, the optical cavity serves as a narrowband filter which preferentially selects either the Stokes (low frequency) or anti-Stokes (high frequency) photons that are generated when a strong control laser is scattered off the mechanical resonator. The second class of device we are studying is focused on applications within this regime.

DEVICE GEOMETRIES

Our material platform is thin (250 nm to 350 nm) stoichiometric Si_3N_4 grown by low pressure chemical vapor deposition (LPCVD) on a silicon substrate. The typical residual stress in these films is tensile with a value of about 1 GPa. Si_3N_4 is primarily chosen due to its wide bandgap, which enables low linear and nonlinear optical losses over the visible and near-infrared wavelength regions, in contrast to silicon, which is opaque at wavelengths below 1 μm and suffers from two-photon absorption at 1.55 μm.

Devices are created using electron beam lithography with a positive tone resist, reactive ion etching through the Si_3N_4 layer, KOH undercutting, and in most cases, liquid CO_2 critical point drying to ensure that the mechanical structures are fully released. Figure 2 shows four different device geometries that we have investigated, involving microdisk and photonic crystal optical cavities coupled to both external and internal mechanical degrees of freedom.

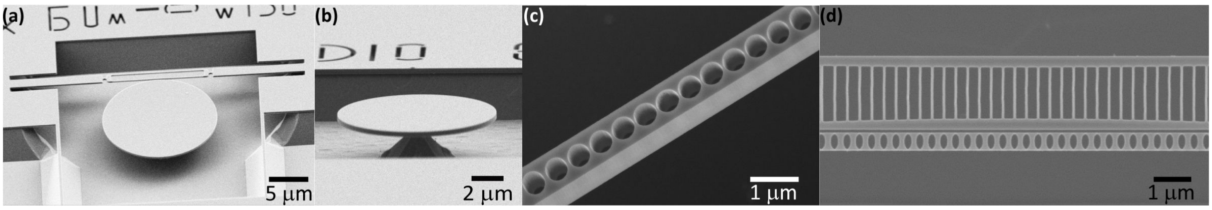

Figure 2. Silicon nitride cavity optomechanical systems. (a) Disk-cantilever. The motion of a doubly clamped, tuning fork cantilever is transduced by an adjacent high-Q microdisk optical cavity. (b) Microdisk cavity for optical wavelength conversion. Whispering gallery optical modes in the 980 nm and 1300 nm bands are coupled to the 625 MHz radial breathing mechanical mode of the disk. (c)-(d) Optomechanical crystal geometries, where GHz phonons strongly interact with 980 nm wavelength photons. In (c), the optical and mechanical modes are localized to the center of a patterned nanobeam. In (d), the breathing mechanical mode of the top patterned beam is coupled to an optical mode that resides in the narrow slot between the top and bottom beams, and whose lateral confinement is determined by the patterning of the bottom beam.

RESULTS

Figure 2(a) shows a scanning electron microscope image of a device being studied within the context of creating high sensitivity force and displacement sensors. Here, the motion of a doubly-clamped cantilever is evanescently coupled to an optical mode of an adjacent microdisk cavity. In this specific structure, a tuning fork geometry has been adopted for the mechanical resonator, in order to reduce clamping losses while maintaining mechanical mode frequencies in the tens of MHz range [8].

Figure 2(b) shows a 10 μm diameter microdisk cavity in which the coupling investigated is that of an optical whispering gallery mode and the radial breathing mechanical mode of the same disk. This system operates in the sideband-resolved regime, with a mechanical mode frequency of 625 MHz that exceeds the optical mode linewidth (typically 150 MHz). Coherent interactions between photons and phonons have been demonstrated in this structure, and because multiple optical modes interact with the same mechanical mode, optomechanically-mediated wavelength conversion has also been realized [7].

Figure 2(c) shows a nanobeam optomechanical crystal. Such devices consist of a defect within an appropriately tailored periodically patterned structure, where the defect serves to simultaneously localize photons and phonons within the electromagnetic and acoustic bandgaps that result from the periodic patterning [9]. In comparison to the microdisk cavity, the observed optomechanical coupling strength in this structure (between a 980 nm localized optical mode and a 4 GHz breathing mechanical mode) is approximately 20 times larger, leading to coherent photon-phonon interactions that have been observed in room temperature and atmosphere [10].

Figure 2(d) shows a new geometry we are developing, which we refer to as a slot-mode-coupled optomechanical crystal [11]. In comparison to the standard nanobeam optomechanical crystal geometry (Figure 2(c)), this structure partially spatially separates optical and mechanical modes, with the mechanical breathing mode resonance of the top beam coupled to an optical mode that is concentrated in the slot between the top and bottom beams. Optical modes in slot mode cavities are generally very sensitive to the precise size of the slot, and indeed, the optomechanical coupling rate in this structure is nearly 3 times stronger than that in a single nanobeam cavity. Perhaps more importantly, the separation of optics and mechanics enables a number of applications in multimode optomechanics, for example, where a second electromagnetic cavity can couple to the mechanical mode.

CONCLUSION

We have developed a variety of cavity optomechanical systems within the Si_3N_4 platform, for both sensing and signal transduction purposes.

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