Integrated III-V Photonic Crystal – Si waveguide platform with tailored Optomechanical coupling

Victor TSVIRKUN[1], Alessandro SURRENTE[1], Fabrice RAINERI[1,2], Grégoire BEAUDOIN[1], Isabelle ROBERT-PHILIP[1], Rémy BRAIVE[1,2*]
[1] Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud,
Université Paris-Saclay, C2N Marcoussis, 91460 Marcoussis, France
[2] Université Paris Diderot, Sorbonne Paris Cité, 75207 Paris Cedex 13, France
* remy.braive@lpn.cnrs.fr

Optomechanical systems, in which the vibrations of a mechanical resonator are coupled to an electromagnetic radiation, have permitted the investigation of a wealth of novel physical effects. Typically for the most of these systems, optomechanical coupling originates from a dispersive dependence of the nanocavity resonance frequency on its geometry, which is modulated by mechanical motion. Dissipative optomechanical coupling consists in the modulation of the lifetime of the cavity photons through the motion of a mechanical oscillator. Very recently, it has been demonstrated that this effect is observed in a wide variety of devices [1-2]. Dissipative couplings may significantly enhance the detection sensitivity in optomechanically-based sensing schemes [3] and open new possibilities in optomechanical control with systems featuring both types of coupling mechanisms [4], where a tailored coupling strength is highly desired.

To fully exploit these phenomena in realistic devices or circuits, the integration of optomechanical resonators on a standard semiconductor platform is required. Here, we propose a novel approach to heterogeneously integrate arrays of two-dimensional photonic crystal defect cavities on top of silicon-on-insulator waveguides (Fig 1a). Added to that, quantum dots (QD) are incorporated in the middle of the III-V photonic crystal membrane with an emission spectrum around 1.55 μm (Fig 1b-d).

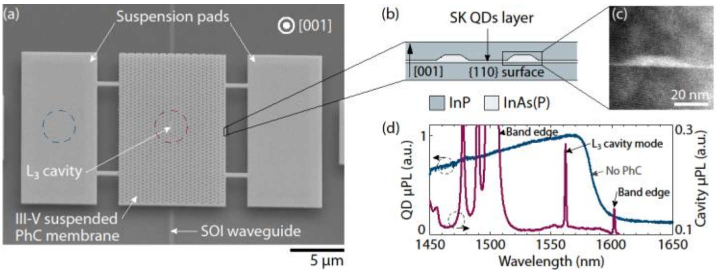

Fig. 1. (a) S.E.M. picture of the photonic crystal membrane with an L3 cavity in the center above a Silicon waveguide. Inside the membrane, InAs(P) Stranski-Krastanov Quantum Dots (SK-QD) have been incorporated (b) in the InP membrane. A T.E.M. image is shown in (c). The emission spectrum of these QD is represented in blue (Fig. 1d) and the spectrum of the L3 cavity is in purple.

We are abled to extract the dissipative and dispersive contributions of the optomechanical coupling of these devices. Tailoring of different contributions was demonstrated using external mean or integrated controls on the geometry of the optical access channel to the nanocavity

Control with the geometry

By performing systematic measurements of the optomechanical response of the fabricated optomechanical resonators as a function of the probe laser wavelength, we showed consistently that the most significant contribution to the optomechanical transduction was of dissipative nature. We observed a different relative sign of the dispersive and external dissipative coupling coefficients by varying the waveguide width (Fig. 2 a-b), which can be regarded as a way to finely tailor the optomechanical coupling strength [5]. Simulations also demonstrate that our system has an additional 'knob' to coarsely tune the optomechanical coupling, represented by suspension height of the membrane.

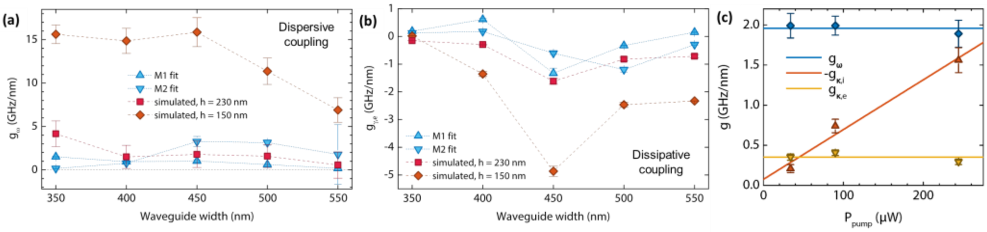

Fig. 2. (a) Dispersive coupling coefficient g_ω and (b) external dissipative coupling coefficient $g_{\kappa,e}$ plotted against waveguide width w_{wg}. Blue, up-pointing triangles: fit of experimental points for the first mechanical mode (M1). Blue, down-pointing triangles: fit of experimental points for the second mechanical mode (M2). Red squares: simulated values, air gap of 230 nm. Orange diamonds: computed values, air gap of 150 nm. (c). Experimental evolution of the different optomechanical coupling strengths with the power of the external non-resonant pump.

External control with QD

We propose the possibility of exerting an external optical control exclusively on the intrinsic dissipative component of the optomechanical coupling within a hybrid optomechanical system by making use of a layer of semiconductor quantum dots. By introducing a non-resonant pump source, we achieve a deterministic modulation of the optical losses of the cavity induced by the quantum dot absorption at the frequency close to the cavity resonance. We show that such an optical modulation is sensitive to the mechanical motion of the device, coupled to the optical cavity resonance via an optomechanical interaction. Non-resonant external pumping of the quantum dots layer can saturate their absorption at wavelengths close to the cavity resonance, thus lowering or eliminating one of the intrinsic loss mechanisms of the cavity. The intrinsic dissipative coupling can be therefore controlled externally (Fig. 2(c)), deterministically and independently of the other coupling mechanisms [6], which in turn can lead to a straightforward implementation of optomechanical resonator capable of reaching the optimal mixed coupling ratio in view of achieving an optimal optical cooling of the mechanical mode [4].

References

[1] M.Li et al, *Reactive Cavity Optical Force on Microdisk-Coupled Nanomechanical Beam Waveguides,* Physical Review Letters, 103, 223901 (2009)

[2] M. Wu et al, *Dissipative and Dispersive Optomechanics in a Nanocavity Torque Sensor*, Physical Review X, vol. 4, pp. 021052, 2014

[3] S. Forster et al, *Cavity Optomechanical magnetometer*, Physical Review Letter, 108 120801 (2012)

[4] T. Weiss et al, *Quantum limits of laser cooling in dispersively and dissipatively coupled optomechanical systems*, Physical Review A, 88, 023850 (2013)

[5] V. Tsvirkun et al, *Integrated III-V Photonic Crystal – Si waveguide platform with tailored optomechanical coupling*, Scientific Report, 5, 16526 (2015)

[6] V. Tsvirkun et al, *External control of dissipative coupling in heterogeneously integrated photonic crystal – SOI waveguide optomechanical system*, Photonics, 3, 52 (2016)