Optomechanical cooling of a glass-fibre nanospike evanescently coupled to a whispering-gallery-mode bottle resonator

Riccardo Pennetta*, Shangran Xie†, Richard Zeltner, and Philip St.J. Russell

Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany

Laser cooling of mechanical degrees of freedom is one of the most significant achievements in the field of cavity optomechanics [1]. Mesoscopic mechanical oscillators with high resonant frequencies (MHz to GHz) are typically favoured for laser cooling because they allow easier access to the sideband-resolved regime. The extension of this technique to the macroscopic scale, which usually involves lower frequency resonances, is not straightforward and several schemes have been proposed over the past decade [2, 3, 4, 5]. Here we report efficient passive optomechanical cooling of the motion of a free-standing waveguide that is dissipatively coupled to a high-Q whispering-gallery-mode (WGM) bottle resonator. The waveguide is an 8 mm long glass-fibre nanospike [6], which has a fundamental mechanical resonance at $\Omega/2\pi = 2.5$ kHz. Upon launching ~250 $\mu$W laser power at an optical frequency close to the WGM resonant frequency, the optomechanical interaction between nanospike and WGM resonator causes the nanospike resonance to be cooled from room temperature down to 1.8 K. Simultaneous cooling of the first higher order mechanical mode is also observed, causing strong suppression of the Brownian motion of the nanospike, observed as an 11.6 dB reduction in its mean square displacement. This result sets a new benchmark on the lowest frequency mechanical motion that can be passively cooled, and represents the first practical application of dissipative optomechanics. The results are of direct relevance in the many applications of high-Q WGM resonators, including nonlinear optics [7], atom physics [8], optomechanics [9, 10], and sensing [11, 12].

Coupling a harmonic oscillator to an optical cavity provides an elegant and powerful means of tailoring its mechanical response [1]. Of particular interest is the regime of “optomechanical cooling”, which exploits this coupling to transfer energy from the mechanical motion to the light field, in the process cooling the centre-of-mass motion of the mechanical oscillator. In most experimental configurations, this optomechanical coupling is dispersive in nature, i.e., the motion of the harmonic oscillator alters the cavity resonant frequency. Under these conditions optomechanical cooling can be very efficient in the sideband-resolved regime, when the mechanical frequency $\Omega$ is much higher than the cavity decay rate $\gamma$ (\(\Omega/\gamma >> 1\)). The quest to observe quantum mechanical effects on the macroscale, in particular quantum-ground-state cooling of micromechanical resonators, has resulted in extensive exploration of the sideband-resolved regime [13, 14]. Increasing the mass or dimensions of a harmonic oscillator implies, however, a decrease in its resonant frequency, which typically sets the lower bound for efficient sideband-resolved cooling in the MHz range. Nevertheless, numerous optomechanical systems operate at low resonant frequencies, for example the mirrors used in LIGO [15], ultracold atomic gases [16], and suspended micro-mirrors [17]. In these systems it has been predicted [2, 18] that “dissipative” optomechanical coupling, in which the motion of the mechanical oscillator modulates the cavity decay rate, could provide an alternative cooling mechanism for all values of $\Omega/\gamma$. So far, however, dissipative cooling has been reported in only one specific system: a SiN membrane placed in a Michelson-Sagnac interferometer [19].

Notably, dissipative coupling is also key to a simpler and extensively explored optical system, namely a free-standing waveguide coupled to a whispering-gallery mode (WGM) resonator. Despite great efforts to engineer optomechanical interactions in this configuration [18, 20, 21, 22], the poor mechanical properties of the waveguides have prohibited demonstration of dissipative cooling. Recently we reported that an appropriately tapered glass-fibre nanospike can provide both adiabatic guidance of light and low-frequency flexural resonances with quality factors Q > 10^5 [6, 23]. In this paper we show that these unique optical and mechanical properties allow passive cooling of the mechanical motion of the waveguide via dissipative optomechanical interactions with a neighbouring WGM resonator. The result is strong suppression of Brownian nanospike motion, indicating self-stabilisation by waveguide-WGM
coupling. Furthermore, given the very low mechanical frequency of the nanospike (2.5 kHz in this experiment), the results prove that dissipative optomechanical coupling is key to achieve efficient cooling even for $\Omega/\gamma$ as low as $10^{-5}$. To the best of our knowledge, this represents a record in the realm of passive optomechanical cooling.

The experimental setup is sketched in Fig. 1a. The nanospike was fabricated by scanning an oxybutane flame along a length of standard single mode fibre (SMF-980) while gently pulling it. The profile of the nanospike was engineered to yield single-mode adiabatic guidance of light at 1150 nm (pump laser) and 1064 nm (probe laser), while preserving high mechanical stiffness [6]. The resulting nanospike was ~8 mm long with a tip diameter of ~700 nm. The fundamental mechanical mode of the nanospike had a resonant frequency of 2.5 kHz and a Q-factor of $1.2 \times 10^5$. The WGM resonator used is a bottle-resonator [24, 25] with a diameter of 46 $\mu$m and an optical Q-factor of $4.1 \times 10^7$ under critical coupling conditions. The experiment was conducted in vacuum ($10^{-5}$ mbar) to eliminate viscous damping by air. Five stepper motors permitted fine-tuning of both the relative position and the orientation between the nanospike and the WGM resonator. An optical micrograph of the system is shown in Fig. 1b. Because of the low transmission of the pump laser in the vicinity of the cavity resonance, a secondary weak (~500 $\mu$W) and non-resonant probe laser was launched to image the mechanical movements of the nanospike tip on a quadrant photodiode (QPD). This permitted two-dimensional reconstruction of the motion of the nanospike with nm-scale spatial resolution. Fig. 1c shows the measured frequency shift and linewidth broadening of the optical cavity as function of its distance from the nanospike for a typical bottle-resonator, indicating the presence of dissipative interactions.

Strong optomechanical cooling was observed when the nanospike was placed in the over-coupled regime with the pump wavelength set very close to, but blue-detuned from, the cavity resonance. The laser detuning was stabilized using the thermo-optical nonlinearity of glass (thermal self-locking) [26]. The resulting mechanical spectra in the vicinity of the fundamental nanospike resonance are depicted in Fig. 2a for increasing values of pump power. A significant drop in the amplitude of the mechanical resonance, accompanied by linewidth broadening, is apparent at higher pump powers. The effective temperature ($T_{\text{eff}}$) of the nanospike "degree of freedom" was estimated by integrating the area underneath the power spectra [1]. As shown in Fig. 2b, an increase of three orders of magnitude in the mechanical linewidth could be measured at only 250 $\mu$W pump power, with a minimum $T_{\text{eff}}$ value of 1.8 K. When the pump power was increased above 250 $\mu$W, the cooling efficiency saturated, probably due to an increase in the ambient temperature induced by residual absorption of the pump light. Note that these results refer to nanospike motion orthogonal to the WGM resonator surface; weaker optomechanical coupling is expected in the direction parallel to the WGM resonator surface. Nonetheless this degree of freedom could still be cooled, as shown in the insets of Fig. 2a and Fig. 2b, with a minimum achievable effective temperature of 68 K.

Since the nanospike mechanical frequencies are much smaller than the cavity linewidth, the cooling should not differ substantially for higher order mechanical modes [1]. Fig. 2c shows the measured power spectra of the first higher order flexural mode, using the pump power as a parameter (same data set as in Fig. 2a). At zero pump power, this mode had a resonance frequency of 6.45 kHz and a Q-factor of 1840. The clear trend observed when increasing the power of the pump laser proves simultaneous cooling of the higher order mode. Because of the lower mechanical Q-factor, the minimum achievable $T_{\text{eff}}$ was 118 K (inset of Fig. 2c). It is worth mentioning that multimode cooling is not easily achievable in the sideband-resolved regime, because it requires precise matching of the laser detuning and the mechanical resonance frequency.

Optomechanical cooling of all the degrees of freedom of nanospike motion resulted in substantial stabilization of its coupling to the WGM resonator. Indeed, at room temperature in the absence of stabilisation, Brownian motion of the nanospike causes fluctuations as high as tens of nm in its distance from the WGM resonator. The consequence is a random fluctuations in the frequency and the linewidth of the WGM, exceeding several MHz at critical coupling (see Fig. 1c). Fig. 3a plots the displacement of the nanospike (after calibrating the response of the QPD) recorded over 100 ms for pump powers of 0 $\mu$W, 10 $\mu$W and 250 $\mu$W. The panel at the right-
hand side compares histogram plots for data collected over 100 s. The reduction of the thermal noise can be clearly observed. At low power, the Brownian motion of the nanospike has a mean-square displacement (MSD) of 530 nm², in agreement with estimates from the equipartition theorem. When the pump power is increased to 250 μW, the value of the MSD drops significantly to 37 nm² (Fig. 3b) – a suppression factor of 11.6 dB.

To highlight the features of dissipative optomechanical interactions, in Fig. 4a we plot the nanospike mechanical linewidth and $T_{\text{eff}}$ as a function of laser detuning. This measurement was performed in the over-coupled regime with 10 μW of pump power. In sharp contrast to traditional dispersive coupling, both cooling and amplification were possible on the blue side of the cavity resonance. The measured mechanical linewidths and $T_{\text{eff}}$ agree reasonably well with theoretical predictions (solid lines). The shaded area in Fig. 4a corresponds to the predicted unstable regime of optomechanical heating. To explore this further, experiments were conducted at higher pump power (60 μW) in the under-coupled regime, when the greater distance between nanospike and WGM resonator permitted measurement of larger mechanical displacements. The result is shown in Fig. 4b. Over the 0-20 s time interval the laser detuning was slowly reduced from 5.0 MHz to 3.5 MHz (upper axis) and thereafter kept constant. Strong exponential amplification of the nanospike motion was observed. Fig. 4c shows a zoom-in of Fig. 4b, comparing the cases of thermally driven (upper panel) and coherently amplified motion (lower panel).

In summary, glass-fibre nanospikes permit observation for the first time of passive cooling of an optical waveguide evanescently coupled to a WGM resonator, in a regime very difficult to access using traditional cavity optomechanical techniques. Accurate knowledge of the position and velocity of the mechanical resonator is not required, in sharp contrast with active cooling schemes [20], which suffer from noise problems at very low temperature. We believe that cooling the nanospike motion could also be highly beneficial for stabilising coupling to an optical cavity well beyond the limits set by thermodynamics. Moreover, dissipative cooling reaches its maximum efficiency close to the cavity resonance at high intracavity power, potentially allowing other experiments to be performed at the same time. Finally, the approach is general and relatively simple and may be applied to any type of optomechanical system with a high enough mechanical Q-factor, allowing efficient optical cooling of low-frequency mechanical oscillators.

Acknowledgements
We thank G. Epple, F. Marquardt and F. Sedlmeir for fruitful discussions.

*riccardo.pennetta@mpl.mpg.de
†shangran.xie@mpl.mpg.de

Appendix

1. Fabrication of the bottle resonator
The bottle resonator was fabricated in a two-step process. First a SMF was thermally tapered to a diameter of ~20 μm, and then the taper was placed in an arc-splicer. Here an electric discharge locally heated up the taper waist, while two sides of the taper were pushed towards each other. Surface tension caused the formation of the prolate shape shown in Fig. 1b. Tuning the arc power and its duration allowed precise control of the resonator diameter and profile. Optical Q-factors in the range of 107 - 108 could be routinely obtained using this technique.

2. Dispersive and dissipative coupling
To confirm the dissipative nature of the optomechanical interactions in the considered system we measured the frequency and the linewidth of the cavity resonance as a function of nanospike distance for a bottle resonator with a diameter of 55 μm. The measured data are shown in Fig. 1c and fit well to an exponential function. We experimentally observed that the frequency shift can vary substantially among different modes, occasionally reaching values so small that they could be hardly measured. On the other hand the broadening of the linewidth did not vary significantly and was always found to be dominant.

References
[1] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity Optomechanics," Rev. Mod. Phys. 86, 1391 (2014).
A. Schliesser, P. Del'Haye, N. Nooshi, K. J. Vahala, A. G. Krause, M. Winger, T. D. Blasius, Q. Lin and M. Scheucher, A. Hilico, E. Will, J. Volz, A. R. Pennetta, S. Xie and P. St.J. Russell, "Tapered T. Ojanen and K. Børkje, "Ground-state cooling of a Micromechanical Oscillator Using Dynamical Systems via cavity-enhanced optical dipole forces," Rev. Sci. Instrum. 87, 1 (2016).

[9] J. Chan, T. P. Mayer Alegre, A.H. Safavi-Naeini, J.T. Hill, A. Krause, S. Groeblacher, M. Aspelmeyer and O. Painter, "Laser cooling of a nanomechanical oscillator into its quantum ground state," Nature 478, 7367 (2011).

[10] A. Schliesser, P. Del'Haye, N. Nooshi, K. J. Vahala, and T. J. Kippenberg, "Radiation Pressure Cooling of a Micromechanical Oscillator Using Dynamical Backaction," Phys. Rev. Lett. 97, 243905 (2006).

[11] A. G. Krause, M. Winger, T. D. Blasius, Q. Lin and O. Painter, "A high-resolution microchip optomechanical accelerometer," Nat. Photonics 6, 11 (2012).

[12] Matthew R. Foreman, J. D. Swaim, and Frank Vollmer, "Whispering gallery mode sensors," Adv. Opt. Photon. 7, 168-240 (2015).

[13] J. Chan, T. P. Mayer Alegre, A.H. Safavi-Naeini, J.T. Hill, A. Krause, S. Groeblacher, M. Aspelmeyer and O. Painter, "Laser cooling of a nanomechanical oscillator into its quantum ground state," Nature 478, 7367 (2011).

[14] J. D. Teufel, T. Donner, Dale Li, J. W. Harlow, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, K. W. Lehnert and R. W. Simmonds, "Sideband cooling of micromechanical motion to the quantum ground state," Nature 475, 7356 (2011).

[15] C. L. Mueller, et al., "The advanced LIGO input optics," Rev. Sci. Instrum. 87, 1 (2016).

[16] K. W. Murch, K. L. Moore, S. Gupta and D. M. Stamper-Kurn, "Observation of quantum-measurement backaction with an ultracold atomic gas," Nat. Physics 4, 7 (2008).

[17] M. R. Vanner, J. Hofer, G. D. Cole, M. Aspelmeyer, "Cooling-by-measurement and mechanical state tomography via pulsed optomechanics," Nat. Communications 4, 2295 (2013).

[18] M. Li, W. H. P. Pernice, and H. X. Tang, "Reactive Cavity Optical Force on Microdisk-Coupled Nanomechanical Beam Waveguides," Phys. Rev. Lett. 103, 223901 (2009).

[19] A. Sawadsky, H. Kaufner, R. M. Nia, S. P. Tarabrin, F. Y. Khalili, K. Hammerer and R. Schnabel, "Observation of Generalized Optomechanical Coupling and Cooling on Cavity Resonance," Phys. Rev. Lett. 114, 043601 (2015).

[20] Y. L. Li, J. Millen and P. F. Barker, "Simultaneous cooling of coupled mechanical oscillators using whispering gallery mode resonances," Opt. Express 24, 1392-1401 (2016).

[21] R. Madugani, Y. Yang, J.M. Ward, V.H. Le and S.N. Chormaic, "Optomechanical transduction and characterization of a silica microsphere pendulum via evanescent light," Appl. Phys. Lett. 106, 241101 (2015).

[22] J. G. Huang, Y. Li, L. K. Chin, H. Cai, Y. D. Gu, M. F. Karim, J. H. Wu, T. N. Chen, Z. C. Yang, Y. L. Hao, C. W. Qiu, and A. Q. Liu, "A dissipative self-sustained optomechanical resonator on a silicon chip," Appl. Phys. Lett. 112, 5 (2018).

[23] S. Xie, R. Pennetta, and P. St.J. Russell, "Self-alignment of glass fiber nanospike by optomechanical back-action in hollow-core photonic crystal fiber," Optica 3, 277-282 (2016).

[24] M. Pöllinger, D. O'Shea, F. Warken and A. Rauschenbeutel, "Ultrahigh-Q tunable whispering-gallery-mode microresonator," Phys. Rev. Lett. 103, 053901 (2009).

[25] G. Kakarantzas, T. E. Dimmick, T. A. Birks, R. Le Roux, and P. St.J. Russell, "Miniature all-fiber devices based on CO2 laser microstructuring of tapered fibers," Opt. Lett. 26, 1137-1139 (2001).

[26] T. Carmon, L. Yang, and K. J. Vahala, "Dynamical thermal behavior and thermal self-stability of microcavities," Opt. Express 12, 4742-4750 (2004).

[27] T. Weiss, C. Bruder and A. Nunnenkamp "Strong-coupling effects in dissipatively coupled optomechanical systems", New Journal of Physics 15, 4 (2013).

[28] F. Cohadon, A. Heidmann and M. Pinard, "Cooling of a Mirror by Radiation Pressure", Phys. Rev. Lett. 83, 3174 (1999).
Figure 1 | Nanospike coupled to a WGM bottle resonator. (a) Sketch of the experimental set-up. NS, nanospike; BR, Bottle resonator, QPD, quadrant photodiode, PD, photodiode. (b) Optical micrograph of the nanospike coupled to a WGM resonator with a diameter of 46 μm. (c) Measured cavity resonant frequency shift (right axis) and linewidth (left axis) as a function of the nanospike-WGM resonator distance for a different resonator. The solid lines are exponential fits of the data. The light blue shaded area marks the over-coupled regime. Inset: measured cavity resonance (blue) and Lorentzian fit (orange) in the vicinity of the critical coupling.
Figure 2 | Optomechanical cooling of the nanospike motion. (a) Measured mechanical power spectrum in the vicinity of the fundamental (flexural) nanospike mode as a function of the pump power. Inset: measured power spectrum for vibration parallel to the surface (see text) with the pump power as a parameter. The solid lines are Lorentzian fits. (b) Mechanical linewidth (left axis) and inferred effective temperature $T_{\text{eff}}$ (right axis) as a function of the pump power. The dashed lines are guides for the eye. Inset: same measurement as in (b) but for vibration parallel to the surface. (c) Measured mechanical power spectrum in the vicinity of the first high order (flexural) nanospike mode with the pump power as a parameter. The solid lines are Lorentzian fits. Inset: linewidth (left axis) and effective temperature $T_{\text{eff}}$ (right axis) of the same mechanical mode as a function of the pump power.
**Figure 3** Self-stabilized coupling to the WGM bottle resonator. (a) Temporal displacement of the nanospike for different launching pump powers. Right panel: histogram plots of the nanospike displacements. (b) Mean-squared displacements of the nanospike as a function of pump power.

**Figure 4** Optomechanical damping as a function of laser detuning. (a) Mechanical linewidth (left axis) and inferred effective temperature $T_{\text{eff}}$ as a function of the pump laser detuning. The dots are data points, while the solid lines are fits of the theoretical model. The yellow shaded indicates the theoretically predicted instability region. (b) Position of the nanospike (blue line) as a function of time when the laser detuning is reduced from 5.0 MHz to 3.5 MHz. After 20 seconds (marked by a dashed line) the laser detuning is fixed at 3.5 MHz. The orange line is an exponential fit of the oscillation envelop. (c) Zoom-in of (b), where the nanospike is thermally driven (upper panel) and coherently excited (lower panel). Note the increase in the scale of the y axis between the two panels.