

Optical Physics

Advanced Techniques and Applications



Vladimir Latinovic

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Optical Physics: Advanced Techniques and Applications

About the Book

This book unfolds the innovative aspects of the advanced techniques used in optical physics. It concentrates on the applications of optical physics, which aids in advancing communications, medicine, manufacturing, and various other sectors. The study of electromagnetic radiation is the primary focus of this field. This book is a compilation of chapters that discuss the most vital concepts and emerging trends in this area of study. The various advancements in optical physics are glanced at and their applications as well as ramifications are looked at in detail. Scientists, students and researchers actively engaged in the field of optical physics will find this book full of crucial and unexplored concepts.

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Vladimir Latinovic holds a master's degree in electrical and electronics engineering. He serves as a senior lecturer and teaches courses on optical communication and optical devices. His research interests lie in the study of optical amplifiers and their applications in telecommunication and computation. Vladimir has presented over 17 papers at national conferences and seminars in the field of electrical and electronics engineering. He also has several articles and book chapters to his credit.

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ISBN 978-1-63238-545-1



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Optical Physics: Latinovic Advanced Techniques and Applications

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Editor: Vladimir Latinovic

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New York

Published by NY Research Press
118-35 Queens Blvd., Suite 400,
Forest Hills, NY 11375, USA
www.nyresearchpress.com

Optical Physics: Advanced Techniques and Applications
Edited by Vladimir Latinovic

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International Standard Book Number: 978-1-63238-545-1 (Hardback)

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Cataloging-in-Publication Data

Optical physics : advanced techniques and applications / edited by Vladimir Latinovic.
p. cm.

Includes bibliographical references and index.

ISBN 978-1-63238-545-1

1. Physical optics. 2. Optics. 3. Optical materials. I. Latinovic, Vladimir.

QC395.2 .O68 2017

535.2--dc23

Printed in China.

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Preface

This book unfolds the innovative aspects of the advanced techniques used in optical physics. It concentrates on the applications of optical physics, which aids in advancing communications, medicine, manufacturing, and various other sectors. The study of electromagnetic radiation is the primary focus of this field. This book is a compilation of chapters that discuss the most vital concepts and emerging trends in this area of study. The various advancements in optical physics are glanced at and their applications as well as ramifications are looked at in detail. Scientists, students and researchers actively engaged in the field of optical physics will find this book full of crucial and unexplored concepts.

This book has been the outcome of endless efforts put in by authors and researchers on various issues and topics within the field. The book is a comprehensive collection of significant researches that are addressed in a variety of chapters. It will surely enhance the knowledge of the field among readers across the globe.

It gives us an immense pleasure to thank our researchers and authors for their efforts to submit their piece of writing before the deadlines. Finally in the end, I would like to thank my family and colleagues who have been a great source of inspiration and support.

Editor

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Electromechanical control of nitrogen-vacancy defect emission using graphene NEMS

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Despite recent progress in nano-optomechanics, active control of optical fields at the nanoscale has not been achieved with an on-chip nano-electromechanical system (NEMS) thus far. Here we present a new type of hybrid system, consisting of an on-chip graphene NEMS suspended a few tens of nanometres above nitrogen-vacancy centres (NVCs), which are stable single-photon emitters embedded in nanodiamonds. Electromechanical control of the photons emitted by the NVC is provided by electrostatic tuning of the graphene NEMS position, which is transduced to a modulation of NVC emission intensity. The optomechanical coupling between the graphene displacement and the NVC emission is based on near-field dipole-dipole interaction. This class of optomechanical coupling increases strongly for smaller distances, making it suitable for nanoscale devices. These achievements hold promise for selective control of emitter arrays on-chip, optical spectroscopy of individual nano-objects, integrated optomechanical information processing and open new avenues towards quantum optomechanics.

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Active, *in situ* control of light at the nanoscale remains a challenge in modern physics and in nanophotonics in particular^{1–3}. A promising approach is to take advantage of the technological maturity of nanoelectromechanical systems (NEMS) and to combine it with on-chip optics^{4–6}. However, in scaling down the dimensions of such integrated devices, the coupling of a NEMS to optical fields becomes challenging. Despite recent advances in nano-optomechanical coupling^{7–10}, *in situ* control of light at the nanoscale with an on-chip NEMS has not been accomplished thus far. In this context, recent work has shown that graphene is an ideal platform for both nanophotonics^{11–15} and nanomechanics^{16–18}.

Here we demonstrate a single device, combining these two platforms. In this device, the transduction between nanomotion and an optical field is due to a strong modification of an emitter's relaxation rate and light emission when graphene is placed in its near field^{14,19–24}, at nanometre-scale distances. The coupling strength increases strongly for shorter distances and is enhanced because of graphene's two-dimensional (2D) character and linear dispersion. As such, this near-field hybrid optomechanical coupling mechanism between graphene and a point dipole is intrinsically nanoscale in comparison with the evanescent coupling involving micron-scale cavities and waveguides in previous lines of work^{4,25–27}. In addition, owing to its electromechanical properties, graphene NEMS can be actuated and deflected electrostatically over few tens of nanometres with modest voltages applied to a gate electrode^{17,28–31}. The graphene motion can thus be used to modulate the light emission, while the emitted field can be used as a universal probe^{19,20,23} of the graphene position.

The coupling between an emitter and graphene can manifest itself in various ways, such as Stark shift³², dipolar-coupling-induced modification of the emission intensity^{20–22,33} or energy (Casimir–Polder³⁴) or as energy transfer to graphene plasmons^{11,14}. In our experiment, we use the dipole–graphene coupling to control the nitrogen-vacancy centre (NVC) emission by the graphene displacement. This effect is due to non-radiative energy transfer (n-RET) and is mediated by dipolar interactions between the emitting point dipole and induced (lossy) dipoles in graphene, as shown schematically in Fig. 1a. As a consequence, it gives rise to a diverging decay rate¹⁹ $\Gamma_G \propto d^{-4}$ of the emitter in the presence of graphene at a separation $d = 5\text{--}50\text{ nm}$. Therefore, the emission is reduced with decreasing graphene-emitter separation. Here graphene offers the advantage to be a 2D gapless broadband energy sink. First, the distance dependence of the energy transfer rate is governed by material-free parameters and wavelength, which can be exploited as a universal nanoruler^{19,20,23}. Second, the enhanced dipolar coupling strength and stronger distance dependence (d^{-4} compared with d^{-3} for bulk materials²⁰) makes the near-field dipolar interaction a more effective and divergent coupling mechanism between a graphene NEMS and a fluorescent emitter.

Results

Hybrid graphene–NVC optomechanical device. To harness near-field dipolar interactions for nano-optomechanical coupling, we propose and demonstrate a novel type of integrated hybrid device as shown in Fig. 1b. Our device consists of a four-layer graphene membrane designed to be suspended some 10–50 nm above a nanodiamond containing one or a few fluorescent NVCs^{35,36}, as shown in Fig. 1c,d. By applying a combination of a d.c. and a.c. voltage to the conducting graphene membrane relative to the doped silicon backgate, we control the graphene–NVC separation and can simultaneously drive the resonator at radio frequencies. Thus, our device enables

electromechanical control of the NVC emission, and complementarily this emission is a transducer of the resonator's nanomotion.

Our hybrid devices are fabricated in arrays (10–100 devices per chip); however, we address them individually. The NVC fluorescence is monitored by a custom-made scanning confocal microscope (Fig. 1f), which simultaneously records the reflectance (Fig. 1e) from the device. These reflection measurements allow us to detect the nanomotion of the graphene resonators by interferometry (*cf.* Supplementary Notes 1, 2 and Supplementary Fig. 1), yielding a map of the mechanical resonance frequency f_m as shown in Fig. 1g. Here f_m depends on drum diameter and can vary between similar drums because of inhomogeneous strain and the presence of ripples as well as photothermal effects³⁷. Together, Fig. 1f,g reveal the colocalization of the emitters and graphene resonators by optical measurements.

Electromechanical control of NVC emission. To quantitatively study and control the near-field interaction between the NVCs and the graphene resonator, we tune the graphene-emitter separation electrostatically. The membrane is attracted towards the NVCs by applying a potential difference V_g^{dc} between the backgate and the graphene drum. Optical interferometry measurements (*cf.* Supplementary Note 2 and Supplementary Fig. 2) show that the static deflection of the graphene scales as $\xi_{\text{static}} \propto (V_g^{\text{dc}})^2$, in agreement with electrostatic actuation. These measurements allow actuation calibration on the order of $1.2 \pm 0.1\text{ nm V}^{-2}$ for the sample shown here (*cf.* Supplementary Note 3). For a given value of V_g^{dc} , the graphene-emitter separation is $d_{\text{G-NVC}}(V_g^{\text{dc}}) = d_0 - \xi_{\text{static}}(V_g^{\text{dc}})$, where d_0 is the initial graphene-emitter separation extracted from the measured device topology (Fig. 1c). Such an electrostatic actuation provides *in situ* and stable control of the graphene deflection from its initial position to the point of contact with the nanodiamond (*cf.* Supplementary Fig. 3).

We use this *in situ* control to extract the separation between the graphene and a localized emitter, a quantity that is difficult to extract using far-field or local probe techniques. Furthermore, we experimentally verify that the graphene-emitter coupling is due to n-RET by measuring the NVC emission as a function of the membrane position. As shown in Fig. 2, we observe a nonlinear reduction of the NVC emission as the membrane is electrostatically deflected towards the nanodiamond. As introduced above, the emitter decay rate $\Gamma_G(d)$ has a nonlinear separation dependence, which induces a separation-dependent total emission strength given as²⁰ (black line in Fig. 2):

$$\phi_G = \frac{\phi_0}{1 + \frac{9v\alpha}{256\pi^3(\epsilon_{\text{eq}} + 1)^2} \left(\frac{\lambda}{d_{\text{G-NVC}}}\right)^4} + \phi_{\text{bg}} \quad (1)$$

Here, ϕ_0 is the emission of a single emitter in the absence of graphene, $v \in [1, 2]$ takes into account the emitting dipole orientation, α is the fine structure constant, ϵ_{eq} is the equivalent relative permittivity of the separating medium (*cf.* Supplementary Note 2) and λ is the emission wavelength, which we take to be the peak wavelength of the NVC emission spectrum (*cf.* Supplementary Note 4 and Supplementary Fig. 4). We fit the data with the emission model shown above where we consider energy transfer from an individual NVC to graphene¹⁹. We consider this interacting emitter to be the NVC closest to the graphene, within a nanodiamond containing an ensemble of one to four NVCs³⁶. Further, we assume NVCs embedded deeper within the nanodiamond to contribute to a fluorescence background ϕ_{bg} (visible in Fig. 2 for small separations), with negligible dependence on the graphene membrane position

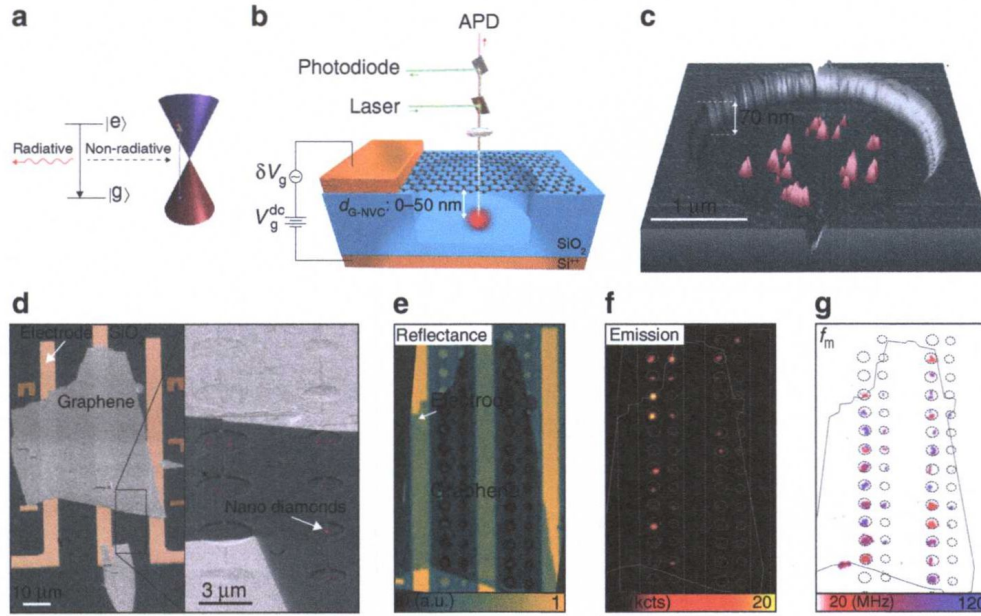


Figure 1 | Graphene-NVC hybrid optomechanical device. (a) Energy diagrams of an optical emitter and graphene at the K point of the Brillouin zone (Dirac cone). For small separations $d_{G-NVC} < 50$ nm, the relaxation of the excited emitter is predominantly due to near-field dipole-dipole interaction by excitation of electron-hole pairs in graphene. (b) Sketch of the hybrid optomechanical device. The graphene resonator is driven and displaced electrostatically by d.c. and a.c. voltages V_g^{dc} and δV_g , while its nanomotion is measured optically via the emitter using single-photon counters (APD) and by interferometry. (c) False colour AFM topology of nanodiamonds (red) deposited in the centre of a hole etched into SiO_2 . (d) False colour scanning electronic micrograph (SEM) of arrays of hybrid graphene devices. The labelled hole corresponds to c. Graphene is closely suspended over the nanodiamonds (0–50 nm) and clamped at the edges of the holes by Vander Waals interactions. (e) False colour confocal reflection map of the same device shown in c at $T = 3$ K. At each laser position, both emission and a mechanical spectrum are recorded, thus providing a spatial map of the NVC emission (f), and the extracted mechanical resonance frequency f_m (g).

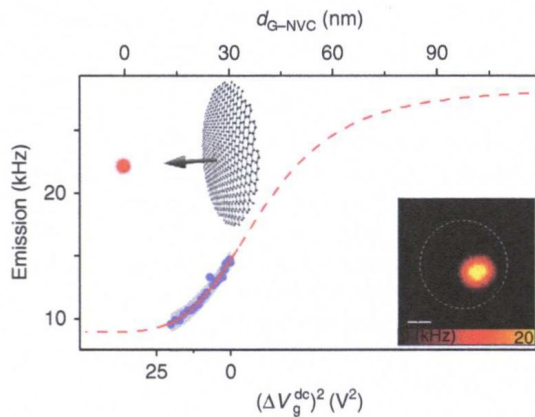


Figure 2 | In situ electromechanical control of dipolar coupling.

Dependence of measured NVC emission intensity (blue) on the graphene-emitter separation d_{G-NVC} , controlled by electrostatic deflection of the membrane. With increasing $(\Delta V_g^{dc})^2$, the membrane approaches the NVC, thereby reducing d_{G-NVC} and quenching the NVC emission. Data can be fitted with an n-RET model (red), which also allows deflection calibration. For large separations, the extrapolated emission rate agrees with measured emission of nanodiamonds in the absence of graphene. The grey band is an uncertainty interval of width 1,500 Hz, estimated in detail in the Supplementary Note 6. Inset: optical emission map of the hybrid system showing localized NVC emission (dashed line: graphene resonator outline).

(cf. Supplementary Note 5 and Supplementary Fig. 5). This background fluorescence inhibits the use of radiative lifetime decay measurements as an alternative method to probe the n-RET separation dependence. However, good agreement of our data with the n-RET model shows that emission measurements

provide an indirect optical probe of the graphene position. Given the assumptions described, the main contributions to the measurement uncertainty—shown in Fig. 2 as a grey band—are the broad emission spectrum as well as the uncertainty in the initial membrane position (cf. Supplementary Note 6). We remark that the observed emission reduction cannot be a result of an interferometric modulation of the excitation intensity because of graphene deflection. Indeed, for our device geometry (oxide thickness and hole depth) the interferometric effect would lead to an increase in the emission on decreasing d_{G-NVC} , in contrast to the measurements shown in Fig. 2 (cf. Supplementary Note 4 and Supplementary Fig. 3 for further discussion).

Nanomotion transduction to NVC emission. Our hybrid device enables high frequency and local control of individual emitters at subwavelength scales. To demonstrate this concept, we show optomechanical transduction of radiofrequency graphene resonator nanomotion to NVC emission, by performing time-resolved emission measurements. During a mechanical oscillation cycle, the graphene-emitter separation d_{G-NVC} periodically varies with an amplitude δz , and the graphene position is imprinted on the NVC fluorescence. To observe this, we drive the resonator capacitively at frequency f_{drive} and simultaneously perform time-correlated single-photon counting of the emitted photons over a few mechanical periods. By repeating such synchronized acquisition, we obtain a histogram of photon arrival times modulated at f_{drive} , as shown in Fig. 3a. As such, this transduction mechanism involves three successive steps: (i) the initial electromechanical actuation of the membrane, followed by (ii) a quasi-instantaneous optomechanical transduction due to n-RET ($\frac{c}{d_{G-NVC}} \gg f_m$, c being the speed of light) and finally (iii) a conversion into a time-resolved electronic signal at the single-photon-counting module.

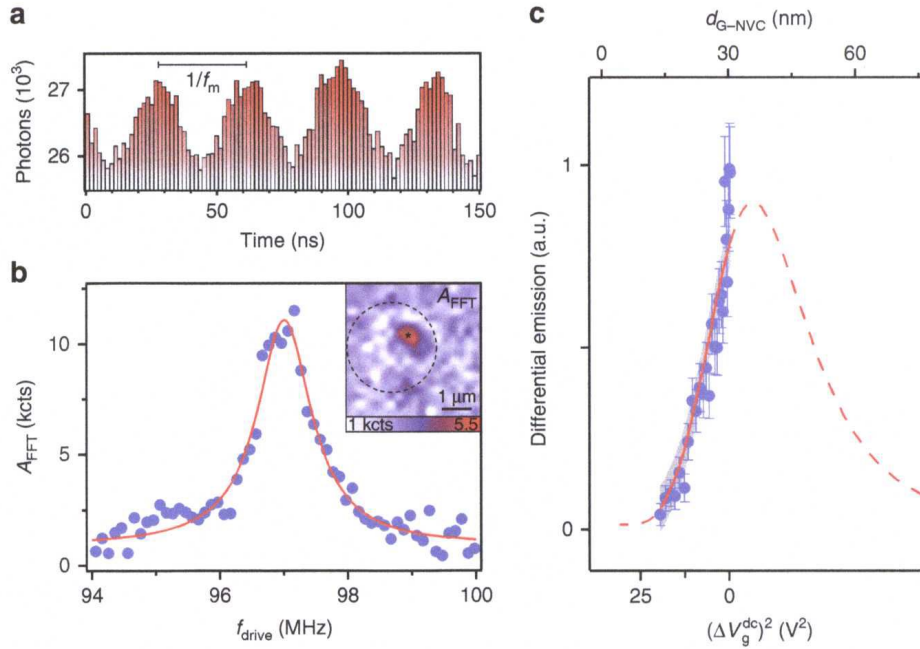


Figure 3 | Graphene nanomotion transduction to NVC emission. (a) Time trace of NVC emission (bars) modulated by a driven graphene membrane oscillating at f_m in its near field. Distance-dependent dipolar emitter-graphene coupling imprints the nanomotion of the graphene membrane on the emission. (b) Mechanical resonance obtained from differential oscillating NVC emission. Each point corresponds to the amplitude of the Fourier component at $f = f_{\text{drive}}$ of the emission time trace (as in a). A Lorentzian fit of the data (red line) yields the same value for f_m as obtained independently by optical interferometry. Inset: spatial map of Fourier component at $f = f_{\text{drive}}$, localized around the emitter position (*). The dashed circle indicates the graphene drum. (c) Dependence of measured (blue) and extrapolated (red) differential NVC emission intensity on the graphene-emitter separation $d_{\text{G-NVC}}$, normalized by the membrane's resonant oscillation amplitude A_m (which increases with V_g , thus reducing the measurement uncertainty for small separations $d_{\text{G-NVC}}$). The grey band is an uncertainty interval (cf. Supplementary Note 6).

Additional interferometric measurements enable calibration of the driven oscillation amplitude to be ~ 1 nm at resonance (cf. Supplementary Note 3 and Supplementary Fig. 4). The optomechanical transduction step is linear for $\delta z \ll d_{\text{G-NVC}}$, resulting in the observed sinusoidal emission modulation despite the nonlinear dependence of emission on $d_{\text{G-NVC}}$.

To reveal the mechanical spectrum of the graphene resonator in the NVC emission, we extract the modulation depth $A_{\text{FFT}}(f_{\text{drive}})$ defined as the Fourier component of the emission time traces at different frequencies f_{drive} . At mechanical resonance, both the amplitude of motion $\delta z(f_m)$ and $A_{\text{FFT}}(f_m)$ are greatest. Indeed, by sweeping f_{drive} through f_m (independently measured by interferometry), we can reconstruct the mechanical spectrum of the graphene resonator (Fig. 3b) through the near-field transduction mechanism.

This transduction strength can be tuned *in situ*. To this end, we record $A_{\text{FFT}}(f_m)$ while varying the stationary separation $d_{\text{G-NVC}}$, as shown in Fig. 3c. Here the differential emission $\Delta A_{\text{FFT}} = A_{\text{FFT}}(f_m)/A_r(f_m)$ is the measured emission modulation amplitude $A_{\text{FFT}}(f_m)$, normalized to the resonant oscillation amplitude $A_r(f_m)$ as obtained from interferometry. This normalization is necessary to compensate the increase in A_r with increasing backgate voltage as $\delta z(f_{\text{drive}}) \propto \chi_m V_g^{\text{dc}} V_g^{\text{ac}}(f_{\text{drive}})$, where χ_m is the mechanical susceptibility. The measurements shown in Fig. 3c reveal that ΔA_{FFT} diminishes with increasing V_g^{dc} . Indeed, while the near-field interaction diverges with decreasing $d_{\text{G-NVC}}$, the observed emission, and thus the transduced signal, is quenched. Our data can be fitted by the derivative of NVC emission with respect to $d_{\text{G-NVC}}$, as expected from equation (1). We find that the largest transduction would be obtained for a separation of 35 ± 3 nm. These results, summarized in Fig. 3c, show that we achieve active control of the optomechanical coupling strength by tuning the separation between a local emitter and a vibrating graphene NEMS.

Finally, we explore the localized nature of the near-field coupling mechanism in the normal plane through time-resolved emission from our hybrid device over the whole area of the driven resonator. A spatial map of $A_{\text{FFT}}(f_m)$ (inset of Fig. 3b) shows a stronger signal at the NVC site, as expected for such n-RET coupling between graphene and a point-like emitter. This observation highlights the intrinsic localization of the interaction, confined within a subwavelength volume. As such, a small ensemble of emitters can be used as a local transducer of the graphene NEMS motion, which enables eigenmode shape reconstruction. On the other hand, driving the NEMS at higher-order mechanical modes, with subwavelength spatial modulations, would allow addressing and coupling to individual emitters distributed over separations unresolvable with far-field optics.

Discussion

Our device also holds promise for dissipative optomechanics experiments. To quantify the dissipative coupling demonstrated here, we use an established formalism^{38,39} to extract a dimensionless dissipative coupling strength $\tilde{B} = \partial_z \Gamma_G z_{\text{zpm}} \Gamma_0^{-1} \sim 10^{-5}$ and the dissipative optomechanical coupling rate $\partial_z \Gamma_G = 6 \text{ MHz nm}^{-1}$, where Γ_G is the decay rate of the emitter in presence of graphene, $z_{\text{zpm}} \sim 65 \text{ fm}$ is the zero-point motion of the resonator and, $\Gamma_0 \sim 30 \text{ MHz}$ is the intrinsic decay rate of an NVC in a nanodiamond⁴⁰ (cf. Supplementary Note 7). This compares favourably with existing dissipative optomechanical devices such as a microdisk coupled to an optical waveguide⁴¹, a graphene resonator coupled to a microsphere optical resonator²⁵ or a photonic crystal nanocavity⁴². The dissipative coupling quantified here takes into account spectral broadening of the emitter we selected. We remark that Fourier limited linewidth emitters such as molecules⁴³ or NVC's in bulk diamonds⁴⁴, in nanocrystals or implanted close to a surface⁴⁵ are readily available.