EXPERIMENTAL PLATFORMS

Cavity Quantum Optomechanics

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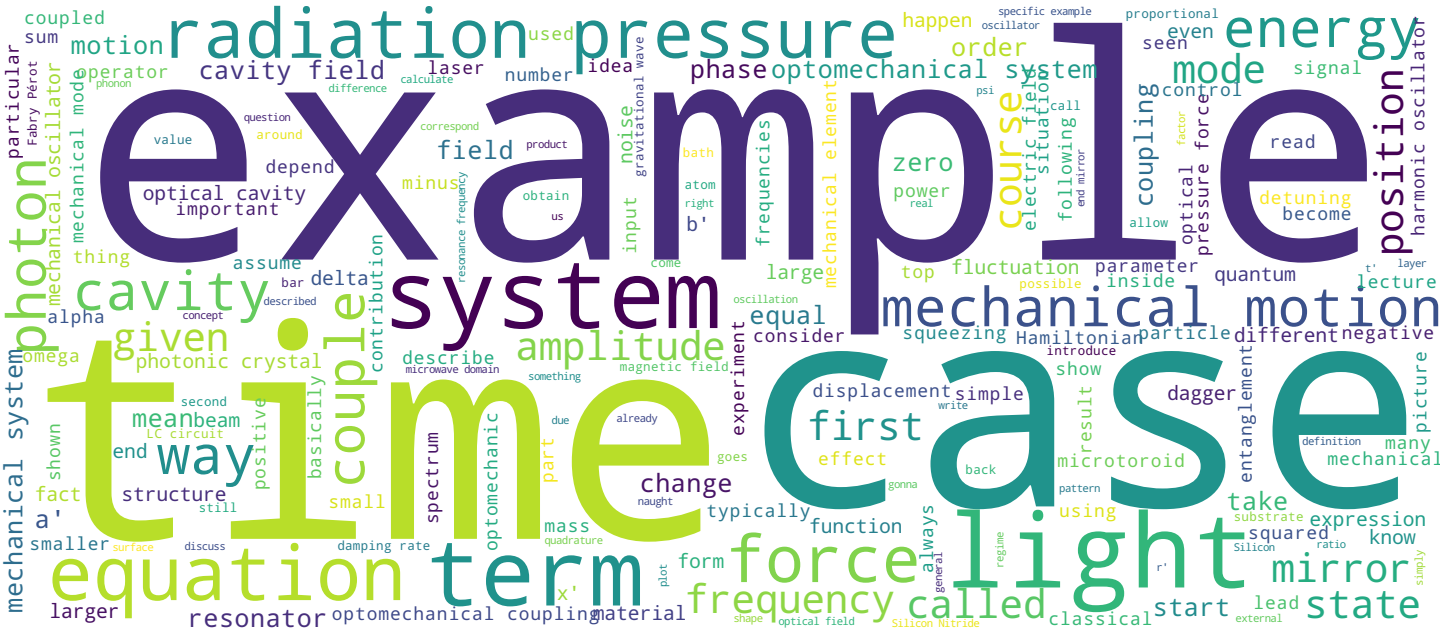

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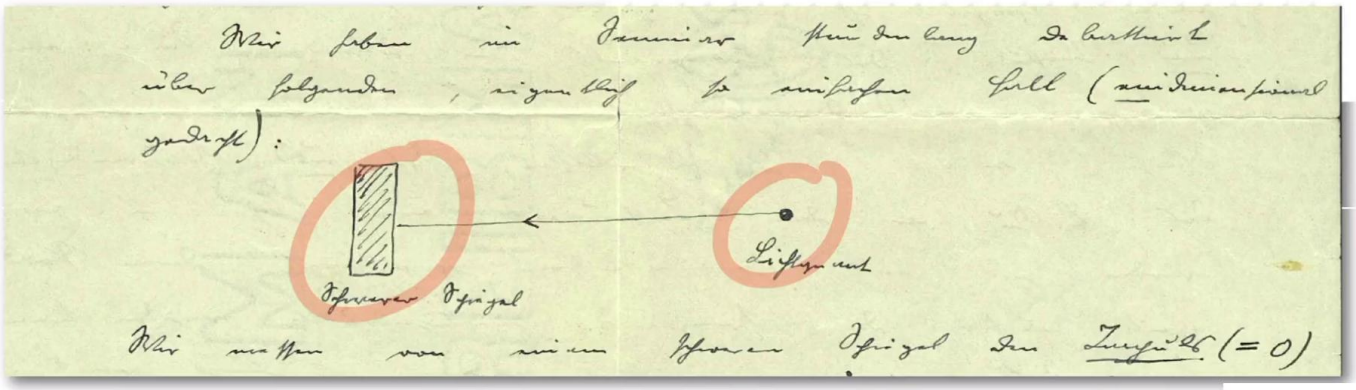
EPFL

EARLY QUANTUM-OPTOMECHANICS: FUNDAMENTAL QUESTIONS

Q: Can quantum mechanics be an adequate description of physical reality?

„[...] Our mirror is a universal measurement tool: [...] momentum and position of the photon are imprinted on the mirror, namely both are registered with accuracies, the product of which can be pushed way below the limit of h [...]“

= OPTOMECHANICAL ENTANGLEMENT!



Schrödinger to Sommerfeld, Dec 11 1931

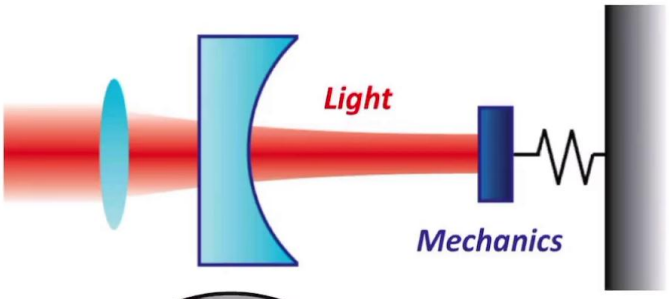
Okay. Welcome back. In this lecture, I will briefly introduce some of the physical platforms used to realize cavity optomechanical systems. We start again with an historical anecdote and yet another attempt to tackle the fundamental Physics question. In the letter to Sommerfeld, Schrödinger asked the following question. What happens when a photon interacts with a heavy mirror? Well, he concludes that the mirror acts as a universal measurement tool in the following sense. I quote: 'Momentum and position of the photon are imprinted on the mirror namely, both are registered with accuracies the product of which can be pushed very below the limit of Planck's constant'. Today, we know that this is a quantitatively correct description of entanglement between light and the mechanical field. And Schrödinger rightfully concludes in his discussion of this optomechanical system that the emergence of such entangled states cannot allow for a complete description of physical reality which, by the way, occurred a few years before the famous paper by Einstein, Podolsky and Rosen.

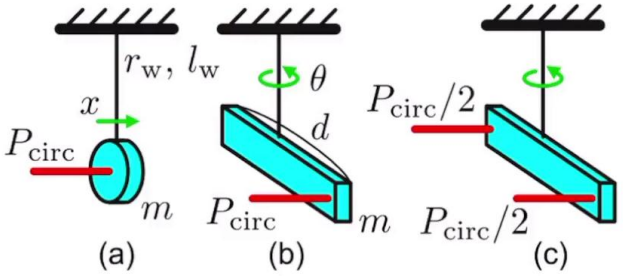
Notes

Summary

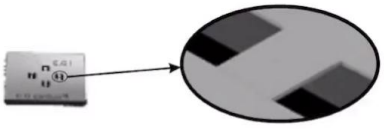
0m 00s

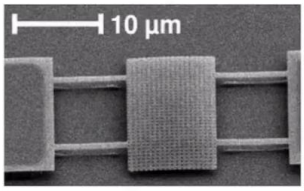
THE “RUBBER CAVITY”

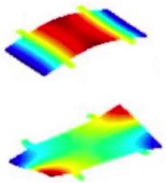




from: EPJD 74, 126 (2020)

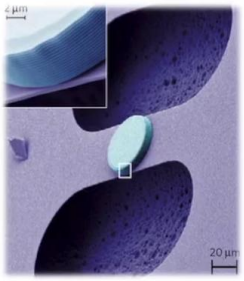


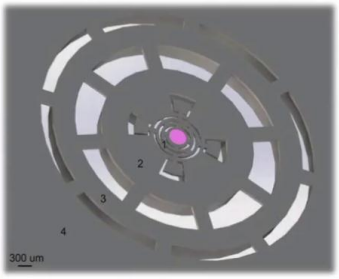




micromirrors (ng – mg)

Nature 444, 67/71 (2006)
Nature Physics 5, 485 (2009)
Optics Lett 36, 3434 (2011)
PRA 97, 033833 (2018)





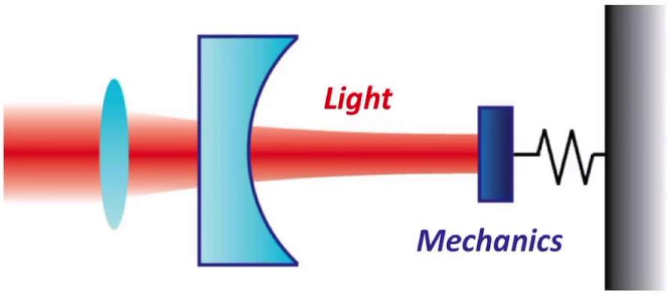
This spirit of direct linear momentum transfer through radiation pressure is carried through in the so-called rubber cavity architectures. Remember the main idea of optomechanical coupling is that motion of a mechanical system effects somehow the optical cavity field. And in that way at the end of the day, it allows us to control both the state of the light through reflective nonlinearities that the light experiences on the state of the mechanics through the radiation pressure interactions and the most simple way to achieve that is in such a Fabry–Pérot cavity where one of the end mirrors is a suspended mechanical system. And such mirrors can be macroscopic like here in the case of LIGO or smaller ones like here in the case of an experiment by the MIT group and typically just coated bulk optics. Going smaller one can also use micromirrors like, for example, in these cases where you have micro optics directly attached to some micromechanical elements or in that case where you have a free-standing photonic crystal membrane instead to reflect light directly out of the plane and can become part of a Fabry–Pérot cavity.

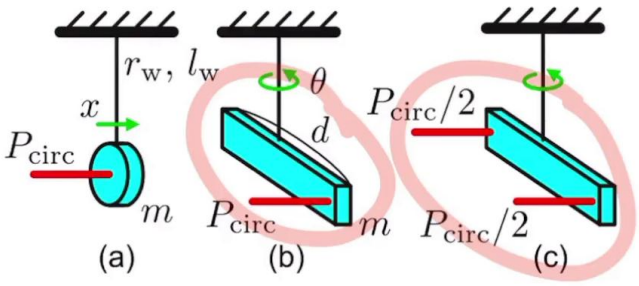
Notes

Summary

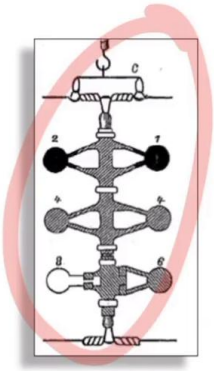
1m 14s

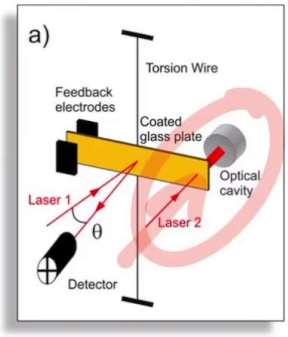
THE “RUBBER CAVITY”





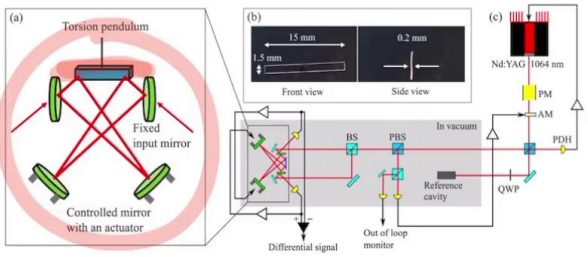
from: EPJD 74, 126 (2020)





torsion pendulum

Ann. Phys. 6, 433 (1901)
Phys. Rev. 13, 307 (1901)
PRA 77, 031802 (2008)
PRA 101, 011802 (2020)



Unlimited somehow in size because at the end of the day in order to prevent the losses to become too large you still have the light beam fit on your mirror here and that's why you're basically bounded from below to some nanograms in your mechanical systems in this rubber cavity geometries. Finally, depending on the shape of the micromirror and the type of suspension, you can also couple two rotational degrees of freedom and realize torsional pendulum. This goes back to the very early demonstrations of radiation pressure by the experiment by Nichols and Hull more than a hundred years ago. Two recent examples are coated glass plate as the micromirror hit here of center and then couples to an optical cavity or a torsional bar that is part of one-end mirror of a ring cavity system.

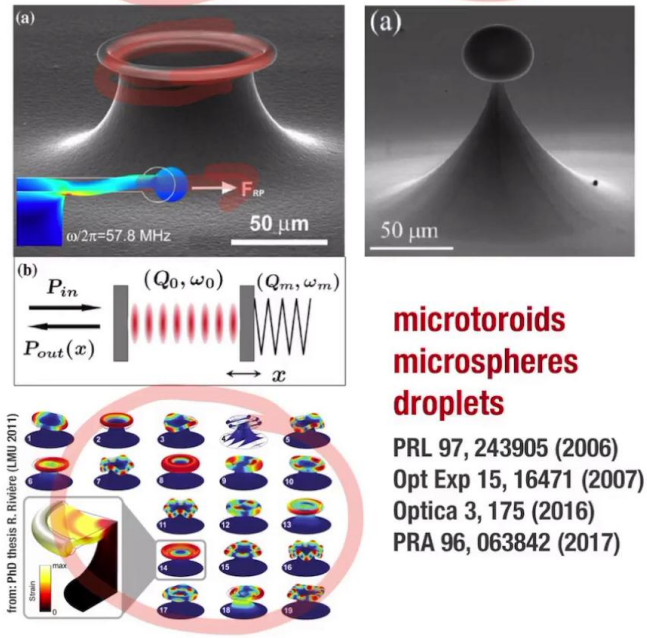
Notes

Summary

2m 42s

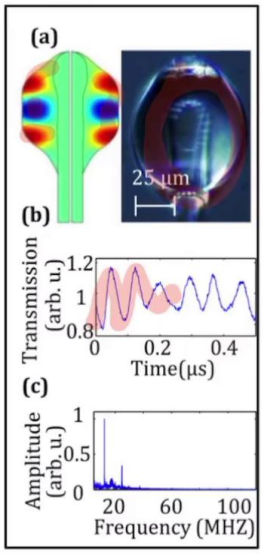
WHISPERING GALLERY MODE RESONATORS

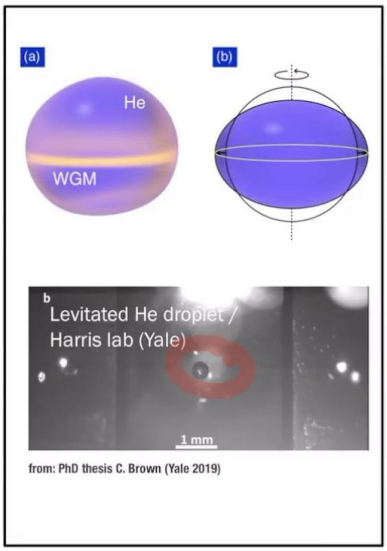
microtoroids | microspheres | supported droplets | levitated droplets



microtoroids
microspheres
droplets

PRL 97, 243905 (2006)
Opt Exp 15, 16471 (2007)
Optica 3, 175 (2016)
PRA 96, 063842 (2017)





Another type of rubber cavity in the wider sense is chip-scale micro optical devices such as microtoroids or microspheres. In these cases light is guided inside the material through total internal reflection in the form of whispering gallery modes. Radiation pressure in the radial direction couples directly to the mechanical breathing motion of the structure. So here are the many examples of the different modes in which these microtoroids here can actually vibrates. In other words, the mechanical motion changes the effective cavity length here of the ring and leads to the wanted optomechanical coupling. The same goes, of course, for liquids. Here are examples shown room temperature liquids directly supported by a surface. You see here the mechanical modes of the liquid hence the transmitted light shows signatures of the mechanical motions directly couples to the mechanical motion. Another goal would be to do that with levitate the droplets. Here's an example of a proposal by the Harris group who levitates magnetically superfluid Helium droplets and optomechanically coupling now would allow to study the motion of such a superfluid in the absence of any support.

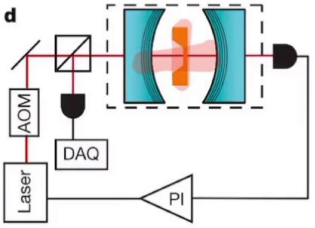
Notes

Summary

3m 42s

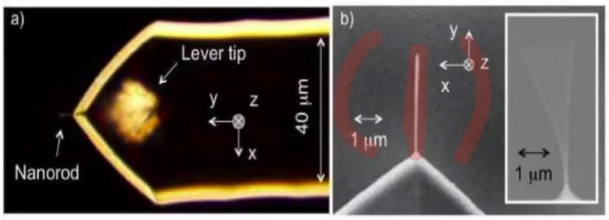
FIXED CAVITIES

suspended resonators ("membrane in the middle")

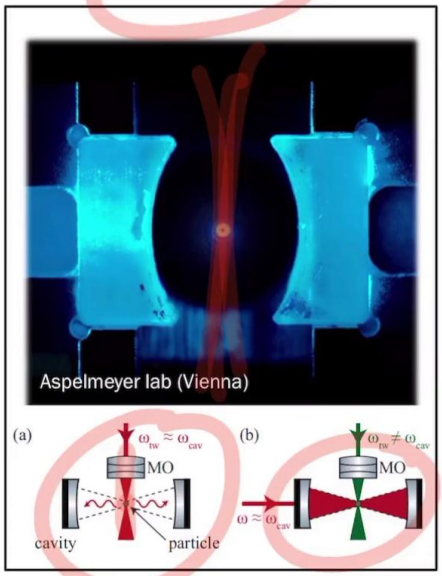


membranes, nanorods, nanospheres

Nature 452, 72 (2008)
Opt Exp 17, 12813 (2009)
PRL 122, 123601/2 (2019)
Science 367, 892 (2020)



levitated particles



Here now leaving the domain of moving cavities and look at another approach namely, using fixed cavities. Hence adding a mechanical elements inside the fix cavity but then cease the radiation field of the cavity. So what happens is that the mechanical element scatters the light back into the cavity depending on where it is located inside the cavity field. This generates the wanted optomechanical coupling. Examples are like here micromechanical membranes that are dispersively coupled to the cavity field just famously called membrane-in-the-middle approach that was introduced originally by the Harris group. One then can also do is smaller structures like nanorods on top of AFM cantilever tips that are then inserted into a fixed cavity at a certain position or nanoparticles trapped in external optical tweezers and then positioned with respect to the cavity field. So in that case the particle can then either couple to a pre-existing cavity field which is an approach that is totally equivalent to the membrane-in-the-middle technique, or it can scatter from the optical tweezer into an empty cavity. This is a method known from Atomic Physics called coherent scattering. We will see in a later lecture that there's some advantages to scattering into an empty cavity compared to having a already filled cavity.

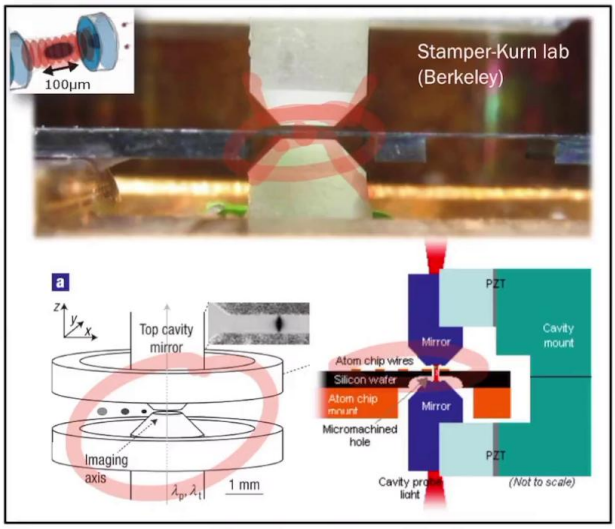
Notes

Summary

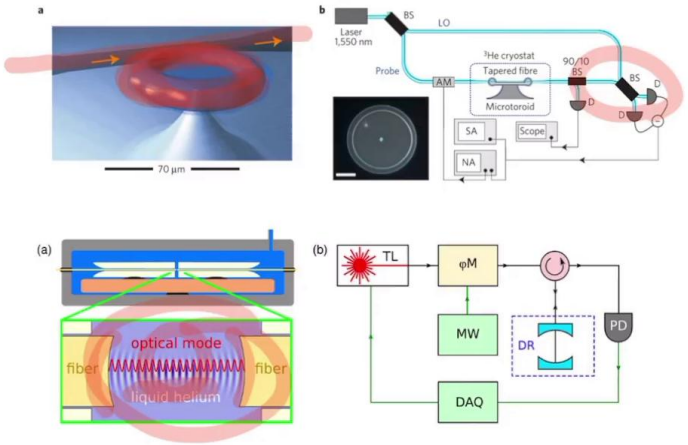
5m 17s

FIXED CAVITIES

atomic ensembles, ultracold gases



superfluid helium



atoms, liquids, superfluids

Nature Physics 4, 561 (2008)
Nature 488, 476 (2012)
Nature Physics 12, 788 (2016)
PRL 122, 153601 (2019)

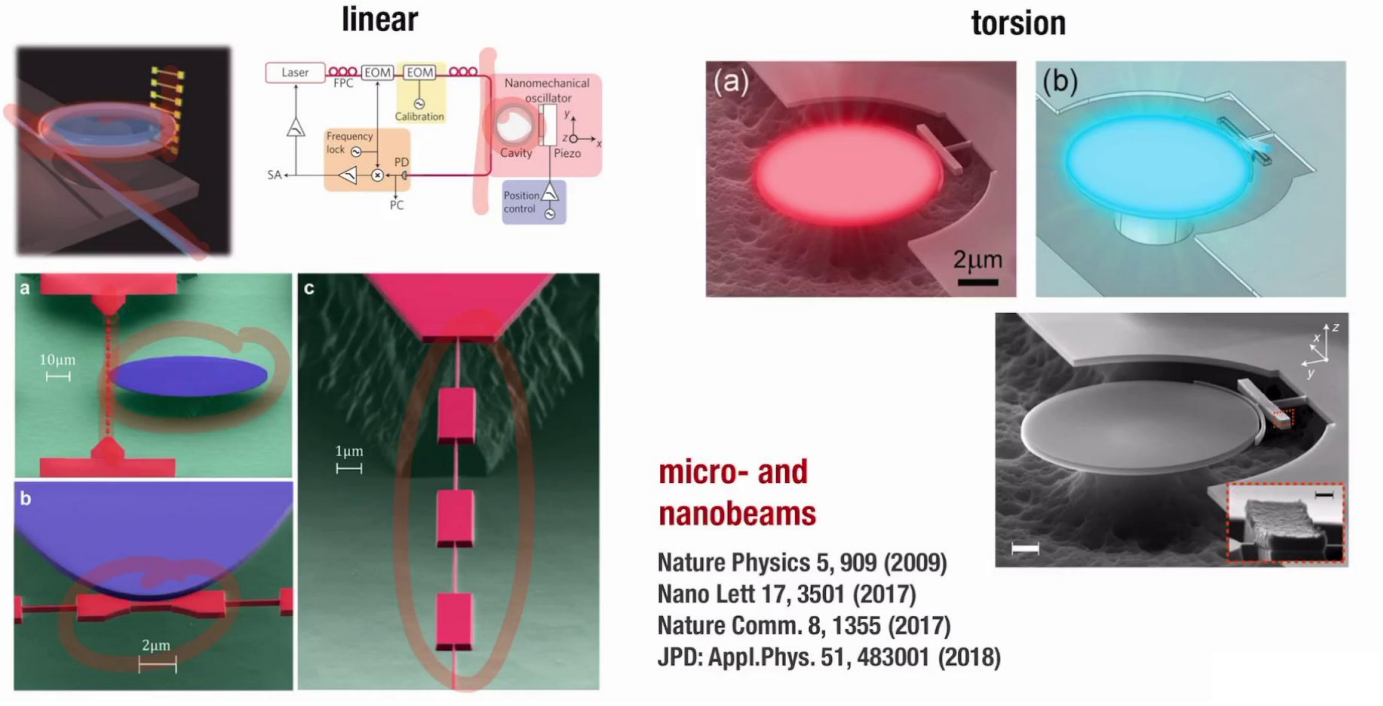
The mechanical element inside such fixed cavity can, of course, also be a cloud of atoms moving along the cavity axis either confined, for example, by a microscopic magneto-optical trap or guided along an atom chip as has been demonstrated here in the Dan Stamper-Kurn lab and here by the way, the cavity mirrors and two of the atoms guided here in the atom chip. In another possibility is that you have atomic gas that exhibits density fluctuations which would effectively change the cavity length and therefore, this couples these fluctuations to the cavity field which is also the idea behind platforms that optically address mechanical excitations in fluids and superfluids. Like here in the case of superfluid Helium, for example, is a film on a microtoroid. We've already seen that so have a tapered fiber that brings the light into the microtoroid, this couples in evanescently exciting the whispering gallery modes and the density fluctuations of the film the Helium film here now couples, of course, to the light that can then be read out. And also another possibility is to have a micro-based fiber-based microcavity here, Fabry–Pérot cavity immersed in a liquid and again the density fluctuations in the liquid directly couple to the optical mode.

Notes

Summary

7m 04s

FIXED CAVITIES: INTEGRATED OPTO-MECHANICS



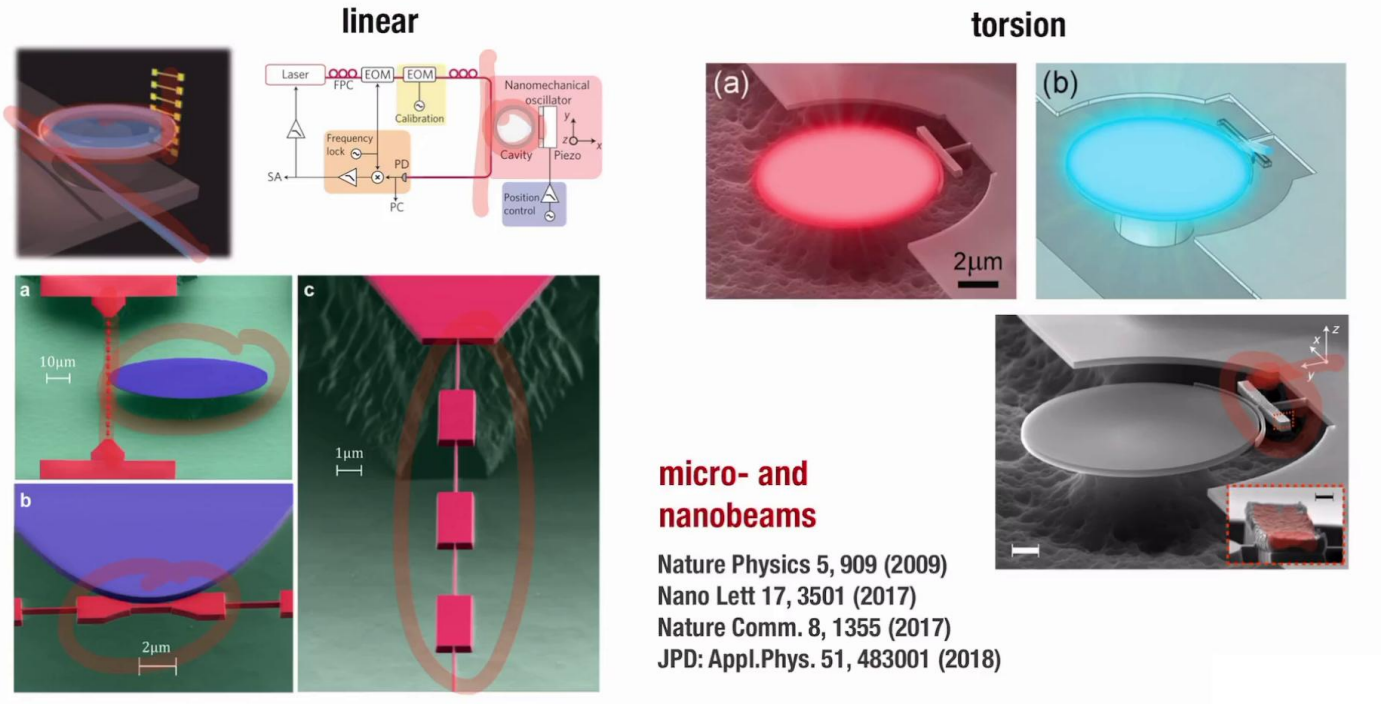
We stay in the domain of micro optics. So using this idea of optical linear field is a very powerful tool to couple all sorts of nanomechanical devices to microcavities. The schematics is as we really saw before, we have a microtoroidal cavity on microdisk resonator that is pumped by some tapered fiber and now through the near-field you can dispersively couple to some rays of nanomechanical oscillators. Here is an example from the lab. This is end picture taken from a Silicon Nitride microdisk and that couples here to a Silicon Nitride nanobeam. You can see a close-up here as this is all fabricated in one hence the strange shape that you see here of the this micropipette nanobeam is to minimize the mechanical dissipation. This will be explained in a later lecture. So effectively what you have here is a 1D phononic crystal to prevent phonons from leaving the structure. The same can be used again also for the torsional motion. So here's an example where this torsional resonator that is coated here with some magnetic material is basically used as a magnetic needle and that's upon interacting with a magnetic field exerts a torque along the y-axis here which results in a modified coupling to the microdisk.

Notes

Summary

8m 43s

FIXED CAVITIES: INTEGRATED OPTO-MECHANICS



So in each case, the either linear or the torsional motion essentially changes the distance between the microdisk and the nanomechanical element and hence the coupling to the evanescent field of the microcavity. This results in a position dependent optical coupling also known as optomechanical interaction as we have introduced early.

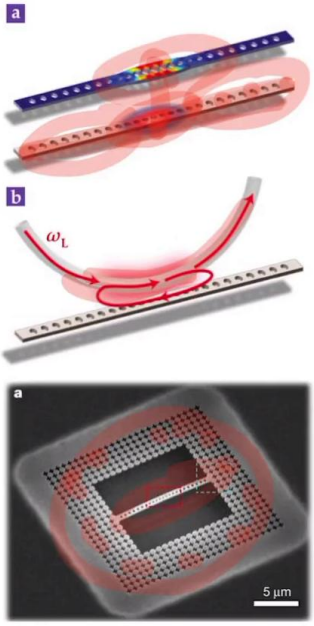
Notes

Summary

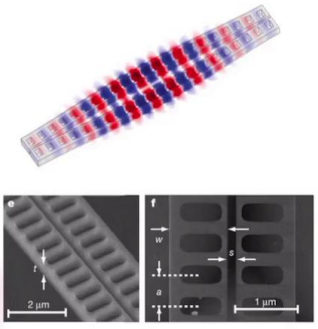
10m 35s

PHOTONIC CRYSTALS

optomechanical crystal



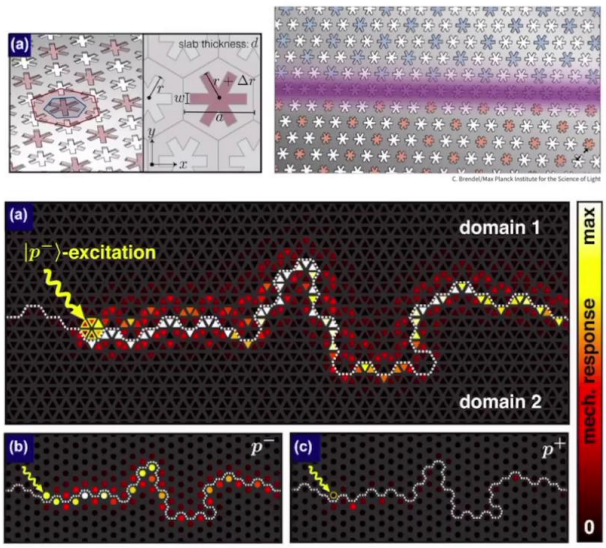
zipper cavity



photonic crystal cavities and arrays

Nature 459, 550 (2008)
Nature 462, 78 (2009)
Nature 478, 89 (2011)
Physics Today 65, 29 (2012)
PRB 97, 020102 (2018)

2d-array



A fully integrated concept is based on photonic crystal cavities that has been put forward by Oskar Painter's group at Caltech. The main idea is the following. You start with a silicon 1D nanobeam and you drill holes in it to produce a periodic modulation in the index of refraction hence creating in effect the mirror on both sides of the beam. If you introduce a defect in the center and launch light through some evanescent coupling mechanism, you strongly localize now the electromagnetic field modes at the center of this structure hence creating an optical cavity on the 1D nanobeam. At the same time this nanobeam exhibits high frequency mechanical motion and some of these modes are strongly co-localized with the cavity mode, thereby enabling strong optomechanical interactions. Here you see an example of a realization of such a structure in Silicon and the pattern here around it is again a phononic shield to improve the mechanical quality of this nanobeam. If you want to couple to the transverse motion of such 1D nanobeams, one idea could be to use zipper cavities where the relative motion of two of these photonic crystals changes the effective evanescent coupling between the two cavities.

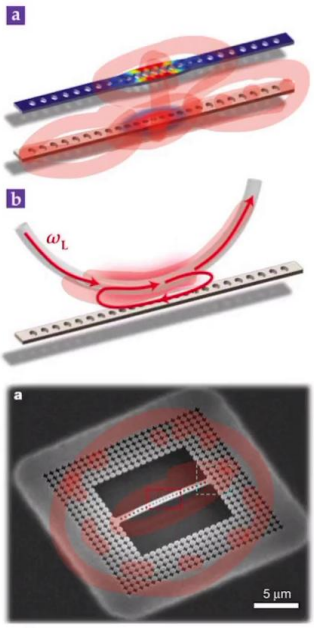
Notes

Summary

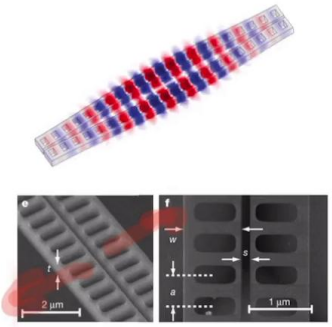
10m 58s

PHOTONIC CRYSTALS

optomechanical crystal



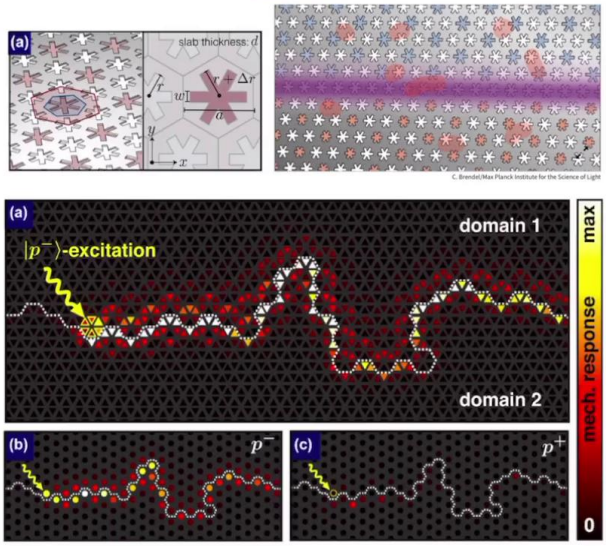
zipper cavity



photonic crystal cavities and arrays

Nature 459, 550 (2008)
Nature 462, 78 (2009)
Nature 478, 89 (2011)
Physics Today 65, 29 (2012)
PRB 97, 020102 (2018)

2d-array

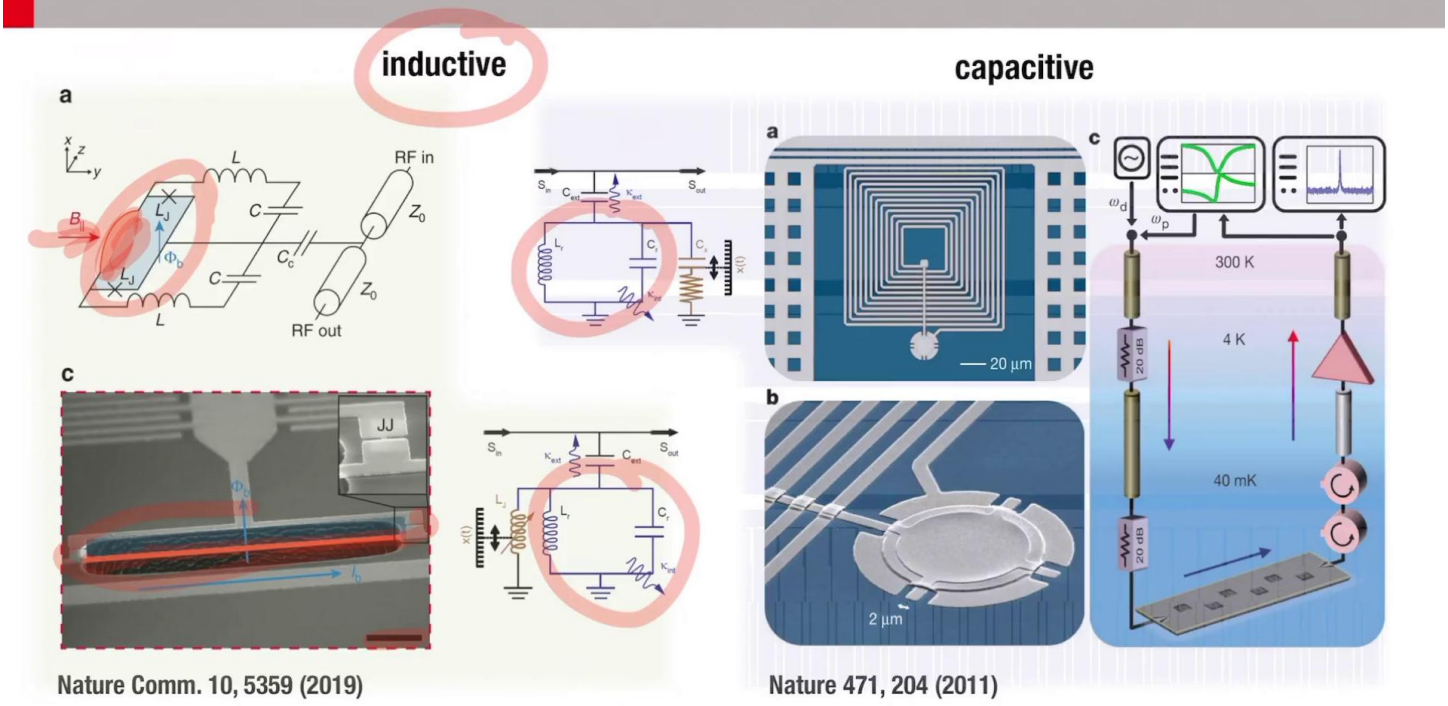


The beauty of this concept of optomechanical crystals is that it can be easily extended to in-plane 2D arrays of optomechanical cavities which essentially means you have a surface and start up drilling holes in it of the right shape and location. Hence this can actually then give rise to complex optomechanical dynamics known from other solid state systems allowing for such things as topological insulators, artificial gauge fields and so on, like we have briefly discussed in the introductory lecture.

Notes

Summary

12m 33s

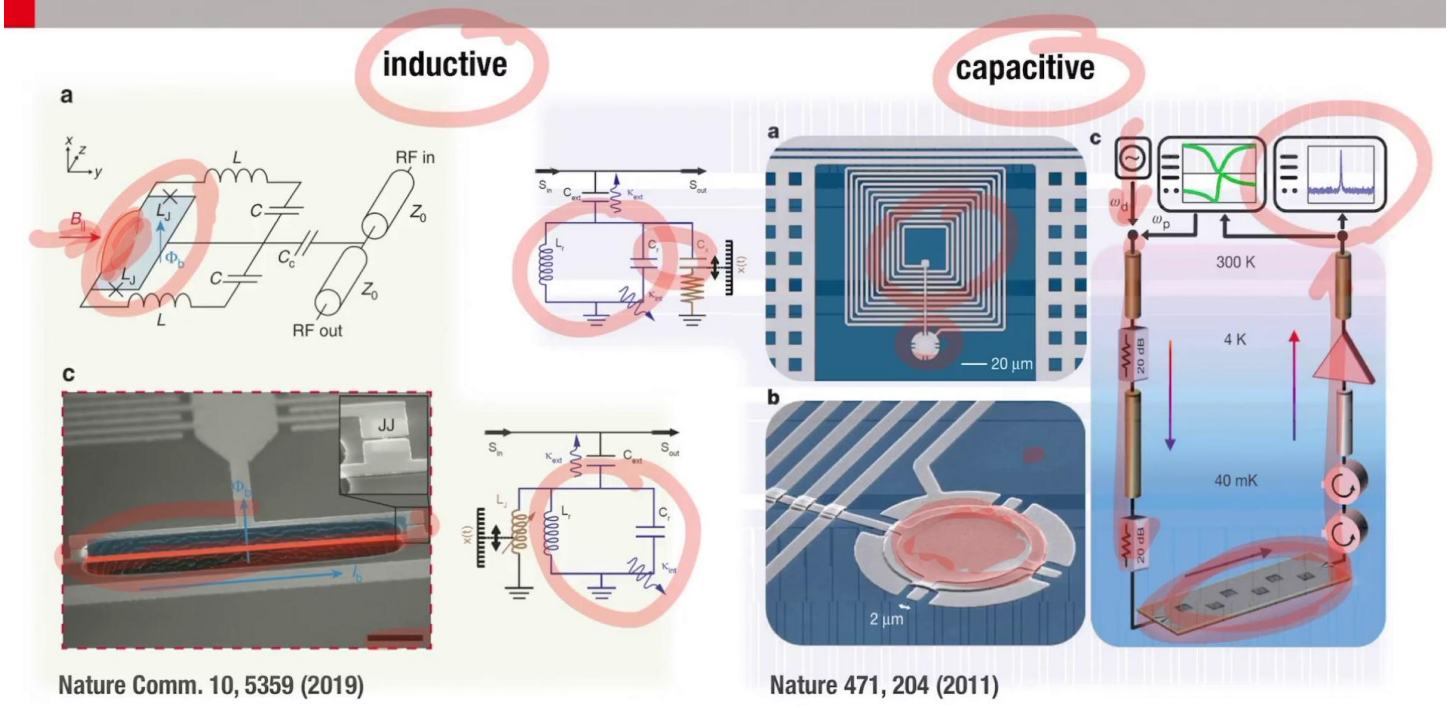


The same ideas can be implemented in the microwave domain. The optical cavity is there simply replaced by a superconducting LC circuit where the inductance and the capacitance is chosen in such a way that the resonance frequency is in the microwave domain. Now mechanical motion can be coupled in different ways now into these cavities. The one possibility is through inductive coupling where the mechanical motion is mediated through a magnetic flux. So in this specific example, an additional skid that is made part of the LC circuit act as an inductor whose inductance depends on the magnetic flux that threads through the skid loop. So mechanical motion out of the plane here of the skid loop. Now can add additional magnetic flux of a external in-plane magnetic field. The larger the motion, the larger the area, the large the flux, the larger the optomechanically induced coupling. So you see here for this realization, a 20 nanometer thick aluminum beam that is a part of this overall skid here and the scale bar here is on the order of three micrometer. Another possibility is capacitive coupling where one modifies the capacitance of the LC circuit through a mechanically moving endplate of a parallel plate capacitor.

Notes

Summary

13m 12s



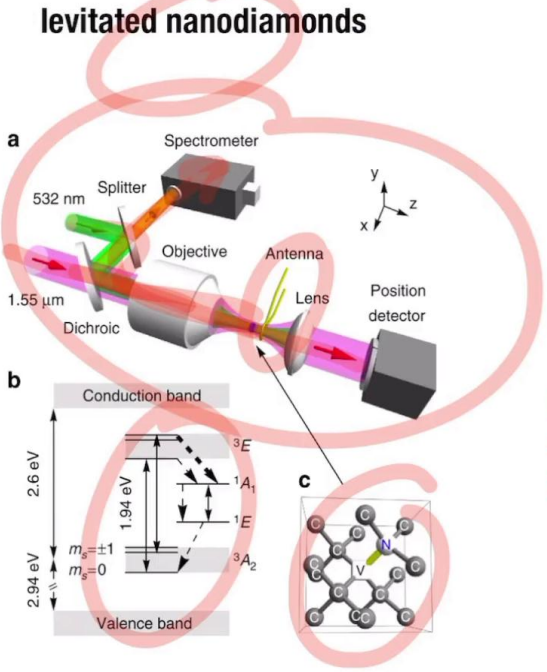
Like in this case where a spiral inductor is linked to a parallel plate capacitor of which one of the end planes is free to mechanically move like a drum. And this again is aluminum on a sapphire substrate. So typical experimental configuration for both cases would be to have the sample circuits immersed at ultra-low temperatures in order to freeze out all thermal excitations of the microwave cavities microwave signals are then fed in through coaxial lines and through cryogenic attenuators down to the fridge, mechanical motion is modulated on the microwave signals which are then fed up again through amplifiers to room temperature where they can then be eventually measured.

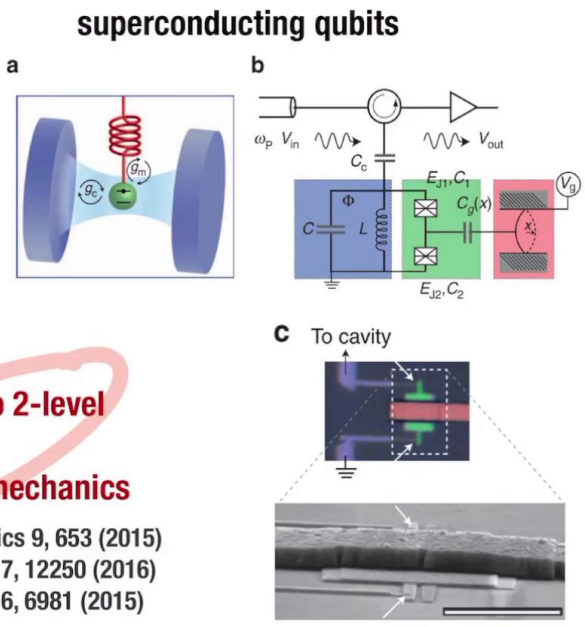
Notes

Summary

14m 53s

HYBRID OPTOMECHANICAL SYSTEMS (EXAMPLES)





Coupling to 2-level systems: Spin-optomechanics

Nature Photonics 9, 653 (2015)
Nature Comm. 7, 12250 (2016)
Nature Comm. 6, 6981 (2015)

As we have seen previously, one of the benefits of using mechanical systems is that they can couple to many other degrees of freedoms and therefore, eventually realize the concept of universal quantum construction. So following up on that idea, we have a brief look here at two specific examples of so-called hybrid optomechanical systems where additional coupling to quantum mechanical two-level systems is realized. One example is levitated nanodiamonds and they are interesting because defects in the carbon lattice of the diamond that typically defects through the nitrogen atoms can result in electronic states that resemble effectively in artificial atom with a well-defined level structure in spin states that can be controlled from microwave and optical fields. Like here in this specific example, the green laser excites the NV centers within the levitated nanodiamond hence the photoluminescence can then be read out. The microwave antenna is used for spin resonance measurements hence then one has another infrared laser that controls and reads out the motion of the nanodiamond. And in this specific example, one could demonstrate that the mechanical motion can be imprinted in the fluorescence of the NV Center and therefore, manipulate the mechanical system's spin state.

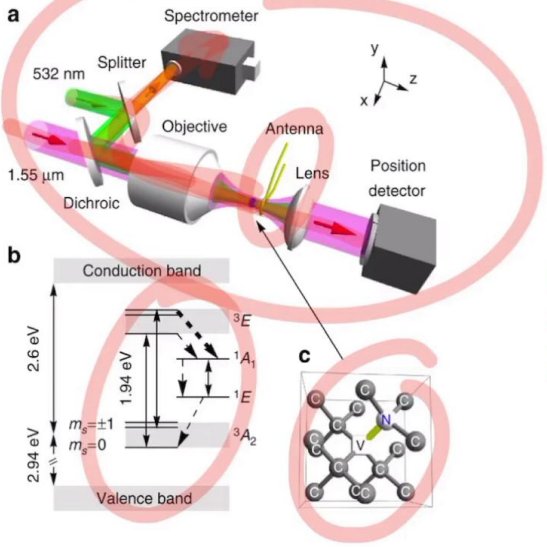
Notes

Summary

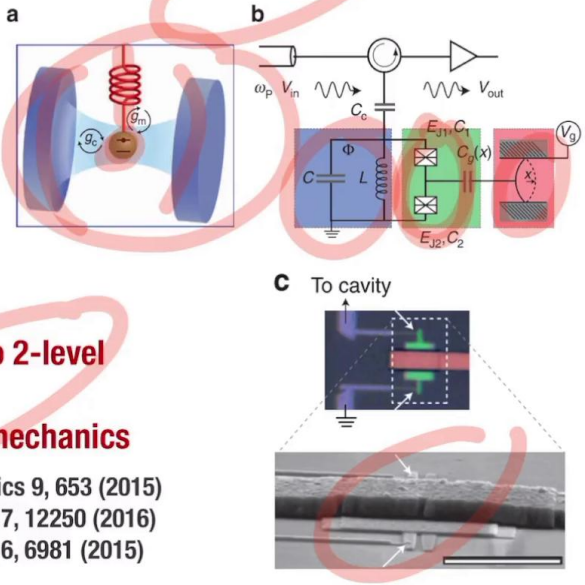
15m 50s

HYBRID OPTOMECHANICAL SYSTEMS (EXAMPLES)

levitated nanodiamonds



superconducting qubits



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Second example is coupling of a microwave cavity through a artificial atom in form of a superconducting qubit that itself is again coupled to a mechanical system. And as we have seen before, the coupling of this superconducting circuit through a mechanical system is achieved again with a movable capacitance like is shown here in this picture. In this specific case, the interesting result was that not only did the system allow here to realize now access to a regime of strong nonlinearities provided by the two-level system but also was the radiation pressure interaction boosted by six orders of magnitude showing the very impressive capabilities of such hybrid systems.

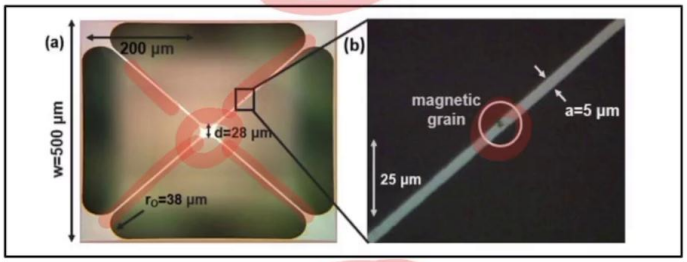
Notes

Summary

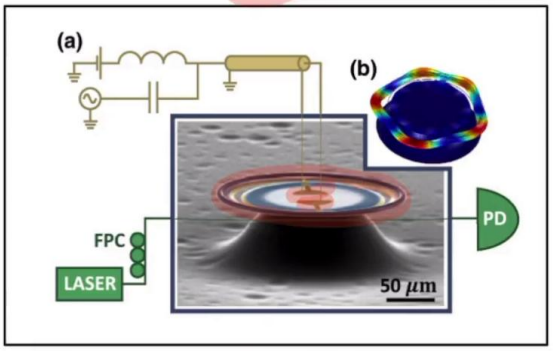
17m 28s

HYBRID OPTOMECHANICAL SYSTEMS (EXAMPLES)

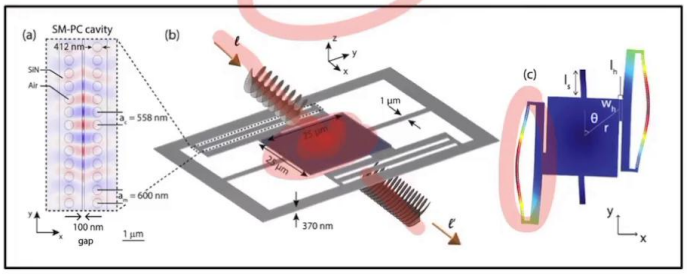
magnetic fields



electric fields



orbital angular momentum



Magneto-Optomechanics
Electro-Optomechanics
OAM-optomechanics

NJP 21, 043049 (2019)
Optica 4, 1196 (2017)
Optics Express 28, 15482 (2020)

Finally, here are examples where the functionalization leads to transduction of magnetic fields, electric fields and even over the momentum of light. So for example, here is a Silicon Nitride small trampoline resonator suspended at these tiny strings on top of which a small magnetic grain is placed that now again can couple to some electronic spin in a nearby structure. Here we have the well-known microtoroidal optomechanical cavity on top of which circular capacitor electrodes are placed in such a way that these now can couple to the radial breathing mode of the microtoroid. And finally, here is a device where this plate here is actuated by change of orbital angular momentum of a beam of light that passes through hence the rotation of this plate leads to a bending that can be read out through the photonic crystal structure embedded here in play. So these are all examples for interfaces between light and other systems, for example, now spins electric fields or other states of light. They are then mediated through the common interaction of the systems with a mechanical element.

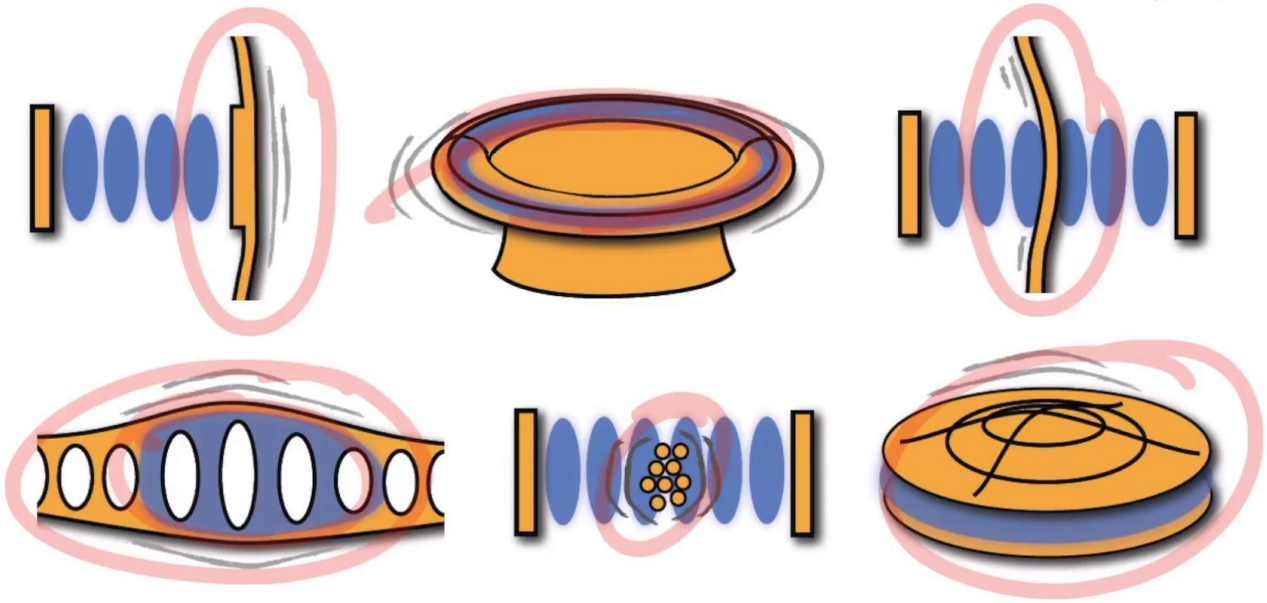
Notes

Summary

18m 25s

SUMMARY: OPTOMECHANICAL PLATFORMS

Rev. Mod. Phys. 86, 1391 (2014)



To sum up, optomechanical platforms come in many different shapes and sizes. At the end of the day, what is required is that mechanical motion needs to couple in one way or the other to an optical or microwave cavity field. So what we have seen as examples was that this coupling was realized by Fabry–Pérot type cavity into the moving end mirror by micro optical systems like microtoroids where the motion, the mechanical motion changes the effective length of the micro optical structures by having mechanical elements directly suspended inside the fixed cavities where such membranes or atoms or single particles can dispersively couple through the cavity field. We have looked at a photonic crystal structures where mechanical motion and electronic fields in a 1D or 2D photonic crystal structure are strongly co-localize or we have looked in a microwave domain at LC circuits where for example, mechanically moving endplate of a plate capacitor can change the cavity frequency. We've also seen several examples of hybrid optomechanical systems and if all of those are not enough for you, well, I guarantee you there is plenty of room to come up with your own systems. Have fun with it.

Notes

Summary

20m 19s