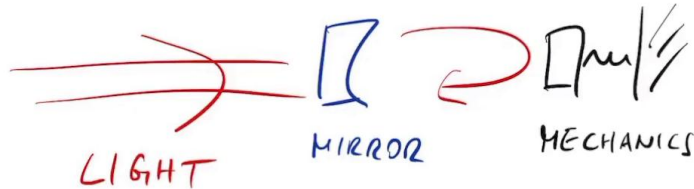


EPFL

CAVITY QUANTUM OPTOMECHANICS

(Cavity) Quantum Optomechanics: a new way to manipulate light and matter on the nano-, micro- and macroscale



Welcome. The goal of this lecture is to provide you with a general motivation for the topic of cavity optomechanics. So what is cavity optomechanics about? The main idea is to have light interact with a mechanical system in a controlled way via radiation pressure typically mediated by an optical or microwave cavity. With this interaction one can now manipulate both the state of light hence the state of the mechanical system. Since mechanical systems come in all shapes and sizes, this establishes a new way to manipulate light and matter on the nano, micro and even macro scale.

Notes

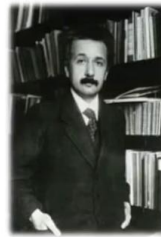
Summary



EARLY QUANTUM-OPTOMECHANICS: FUNDAMENTAL QUESTIONS

Q: What is the nature of radiation?

A: Radiation pressure comprises BOTH particle- AND wave-character!!



Physikalische Zeitschrift 10, 817 (1909)

Über die Entwicklung unserer Anschauungen über das Wesen und die Konstitution der Strahlung; von A. Einstein.

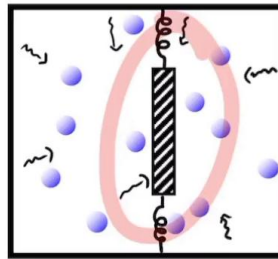
(Vorgetragen in der Sitzung der physikalischen Abteilung der 81. Versammlung Deutscher Naturforscher und Ärzte zu Salzburg am 21. September 1909.) (Vgl. oben S. 417.)

$$\overline{\Delta^2} = \frac{1}{c} \left[h \nu + \frac{c^3}{8\pi \nu^2} \right] d\nu f \tau.$$

mechanical position fluctuation

particle

wave (interference)



“...a plate of solid substance, which is only freely movable perpendicular to its plane...completely reflecting on both sides...”

“... the radiation will exert a pressure on both sides of the plate...”

Probably the first historic example for the usefulness of quantum optomechanical interactions goes back to Einstein who addressed a very fundamental physics question in the year 1909 at a presentation he gave in Zeitschrift. This was at a time when the light quantum hypothesis was still widely debated in the physics community. In order to obtain more insight into the nature of radiation, he suggested a simple Gedankenexperiment in which a moving mechanical oscillator with perfectly reflecting surfaces was kept inside a black body cavity filled with gas. The gas transfers energy to the mirror via collisions. The mirror transfers energy to the radiation field via radiation damping. The question now was, how does the energy transfer from the radiation field to the mirror have to look like in order to achieve thermal equilibrium between gas, radiation and mechanics? The answer lies in the radiation pressure-induced mechanical position fluctuations which after analysis contain two contributions. One that is well known from the domain of classical physics and can be traced back to the wave nature of radiation. Simple interference that leads to fluctuating radiation pressure contributions.

Notes

Summary



0m 47s

EARLY QUANTUM-OPTOMECHANICS: FUNDAMENTAL QUESTIONS

Q: What is the nature of radiation?

A: Radiation pressure comprises BOTH particle- AND wave-character!!



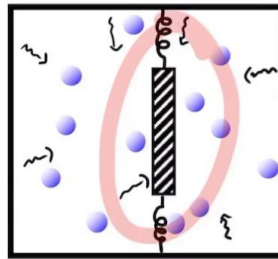
Physikalische Zeitschrift 10, 817 (1909)

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$$\overline{\Delta^2} = \frac{1}{c} \left[\underbrace{h \rho \nu}_{\text{particle}} + \underbrace{\frac{c^3}{8\pi} \frac{\rho^2}{\nu^2}}_{\text{wave (interference)}} \right] d\nu f\tau.$$

mechanical position fluctuation



"...a plate of solid substance, which is only freely movable perpendicular to its plane...completely reflecting on both sides..."

"... the radiation will exert a pressure on both sides of the plate..."

The second contribution, however, is one that is due to the particle nature of light. In other words, both the wave and particle character of radiation are necessary to obtain a complete description of this optomechanical system.

Notes

Summary



2m 13s

ENTERS QUANTUM OPTICS: FROM NUISANCE...

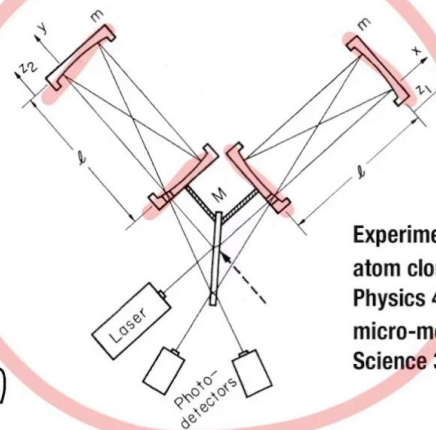
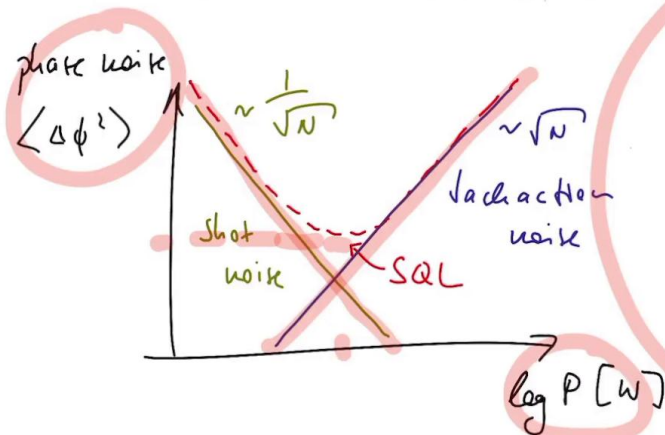
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

PRL 45, 75 (1980)

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational waves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.



Experimental demonstrations:
atom cloud: Murch et al., *Nature Physics* 4, 56 (2010)
micro-membrane: Purdy et al., *Science* 339, 801 (2013)

However, not all optomechanical radiation pressure effects turned out to be useful. By the 1960s, it was clear that quantum mechanics poses an ultimate limit on the intensity fluctuations in the laser beam, the so-called shot noise. With the appearance of large-scale interferometers for gravitational wave detection appeared also a pressing question. How bad is shot noise actually for sensing? One of the seminal papers here by Carl Caves addresses exactly this question. How do quantum mechanical radiation pressure fluctuations disturb the measurement of the position of the free masses in such large-scale interferometers? An intuitive answer is provided by looking at the measurement noise as a function of the laser power inside the interferometer. While the relative intensity fluctuation and hence the noise goes down with increase in laser power, the backaction noise imparted by radiation pressure fluctuations on the mechanical systems actually go up. As a consequence, there's a minimal phase noise that can be reached at a certain laser power when the integration time is kept constant. This is called the Standard Quantum Limit of continuous detection.

Notes

Summary



ENTERS QUANTUM OPTICS: FROM NUISANCE...

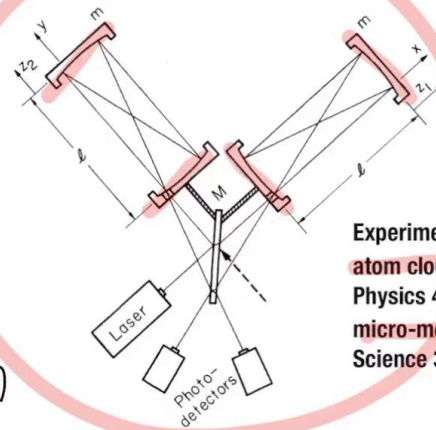
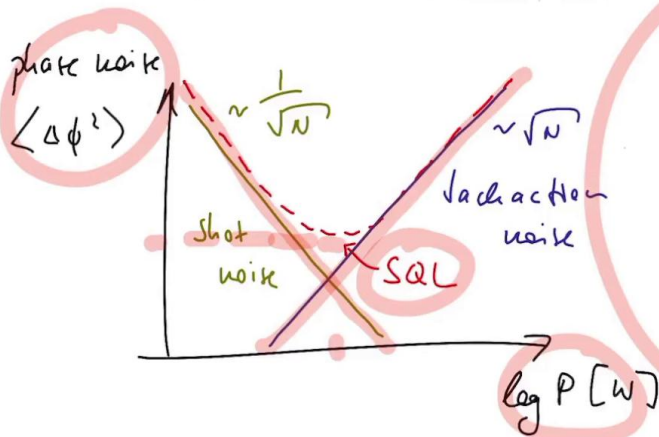
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Experimental demonstrations:
atom cloud: Murch et al., Nature Physics 4, 56 (2010)
micro-membrane: Purdy et al., Science 339, 801 (2013)

And only recently this has been experimentally demonstrated namely, mechanical fluctuations dominated by quantum mechanical radiation pressure. In one experiment an atom cloud being kept inside an optical cavity was monitored. In the other case, a micro membrane inside an optical cavity driven by radiation pressure fluctuations was observed.

Notes

Summary



3m 49s

Article

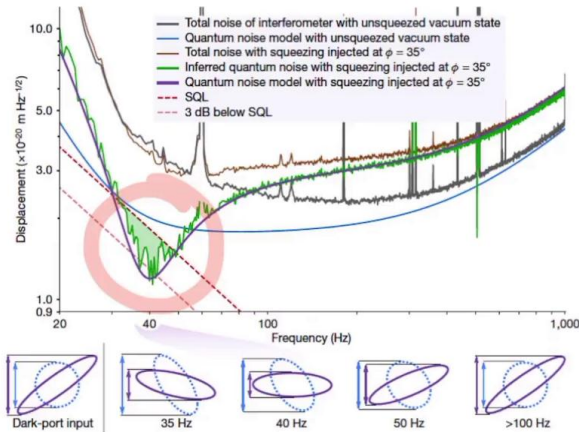
Nature 583, 43 (2020)

Quantum correlations between light and the kilogram-mass mirrors of LIGO

<https://doi.org/10.1038/s41586-020-2420-8>

Received: 3 February 2020

Haojun Yu^{1,2}, L. McCuller^{1,2}, M. Tse¹, N. Kijbunchoo², L. Barsotti¹, N. Mavalvala¹ and other members of the LIGO Scientific Collaboration*



- surpassing the standard quantum limit (SQL) by using optomechanical interactions
- early pioneering works by Braginsky



Not everything is a nuisance. With passing time researchers have learned to control the interactions by making use of the dynamics provided by the cavities. In this specific recent example of the LIGO gravitational wave detectors, a combination of squeezed input light and ponderomotive squeezing through optomechanical interactions inside the long-baseline cavities of LIGO resulted in measurement capabilities even below the Standard Quantum Limit showing the added value of cavity optomechanics for enhanced sensing.

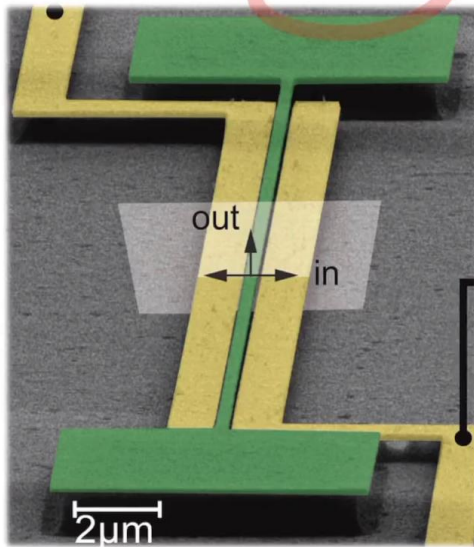
Notes

Summary



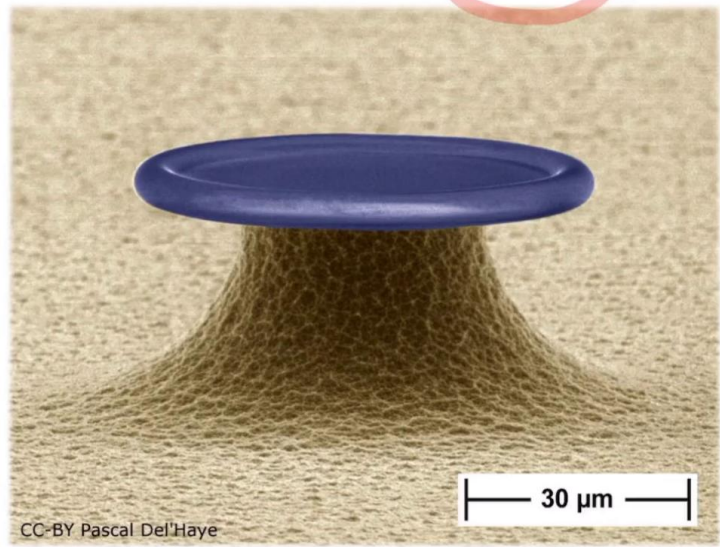
GETTING SMALLER

Nano- and micro-mechanics



Weig group, PRL 118, 254301 (2017)

Chip-scale (integrated) optics



Kippenberg group, SPIE (2011)

The early ideas for utilizing the effects of radiation pressure go back to Vladimir Braginsky in the 1960s. One of the main reasons for today's success and widespread use was the continuous militarization of both mechanical and optical systems. By the turn of the century and millennium, nanomechanics and integrated optics has become widely available and with it the access to radiation pressure effects.

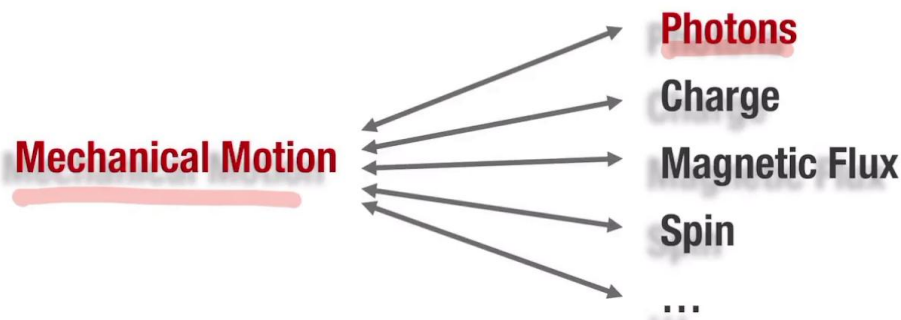
Notes

Summary



4m 54s

NEW APPLICATIONS: (QUANTUM) TRANSDUCERS



Example: Mechanical Quantum Bus

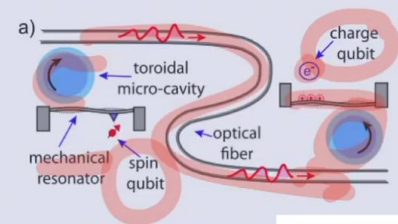
PRL 105, 220501 (2010)

PHYSICAL REVIEW LETTERS

week ending
26 NOVEMBER 2010

Optomechanical Transducers for Long-Distance Quantum Communication

K. Stannigel,¹ P. Rabl,^{2,1} A. S. Sørensen,³ P. Zoller,¹ and M. D. Lukin^{2,4}



Cavity optomechanics enables a whole range of new applications. One striking advantage, for example, of a mechanical solid-state system is that it can be functionalized so you put a mirror on a mechanical system, you couple the photons. You put the conductor on it, you couple the charge and so on and so on. You get the idea. In that way the mechanical system can serve as a bus between light and other degrees of freedom that would otherwise not directly couple to photons or interact with each other easily. In addition, photons can be easily detected and they can be sent over large distances. A beautiful example here is using a mechanical quantum bus to achieve long distance quantum communication between spin degrees of freedom and charge degrees of freedom. For example, by coupling the spin qubit through a mechanical resonator coupled the cavity to photons that propagate over long distance and then the quantum information can again through an optomechanical transduction be transferred onto the charge qubit.

Notes

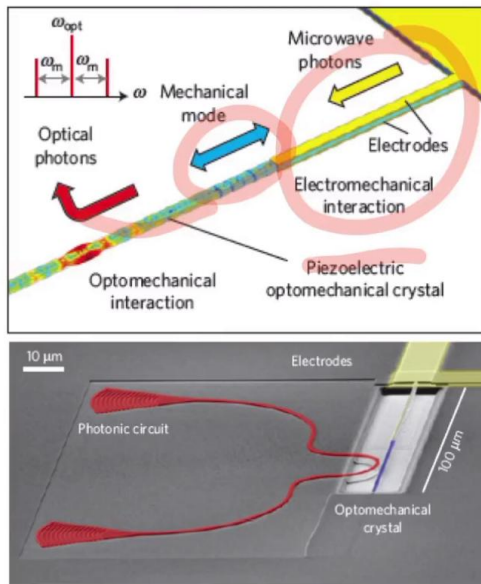
Summary



5m 22s

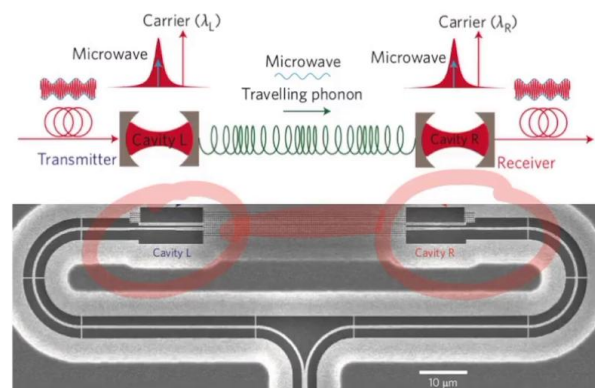
LINKING QUANTUM COMPUTERS

Microwave-to-Optics Conversion



Nature Physics 9, 712 (2013)

Phonon Routing



Nature Photonics 10, 489 (2016)

see also:

Nature Physics 10, 321 (2013)

NJP 21, 123013 (2019)

Nature Physics 16, 69 (2020)

Another application example is directly linked to one of the outstanding challenges in quantum computing technology. How to interconnect microwave-based quantum processors? In the ideal case, a microwave photon is converted into an optical photon which can then be sent over long distances. Optomechanics provides a possible solution. One possibility is that microwave signals are converted into mechanical energy through an electromechanical interaction, for example, by using a piezoelectric material. This mechanical signal can then be converted into optical information through an optomechanical interaction. Exploiting microwave phonons even allows to get rid of piezoelectric materials. In this specific example, a pair of optomechanical cavities is interconnected via a phonon waveguide. In that case, one can actually establish from microwave signal processing that relies only on phonon routing and in that way form interacting microcircuits of photons and phonons.

Notes

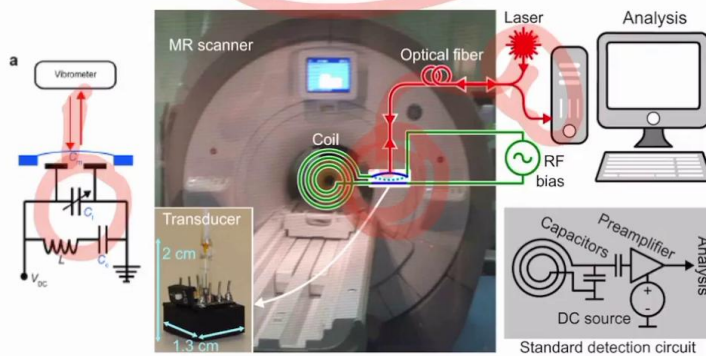
Summary



QUANTUM SENSING

Optomechanical Magnetic Resonance Imaging (MRI)

Electro-Opto-Mechanics

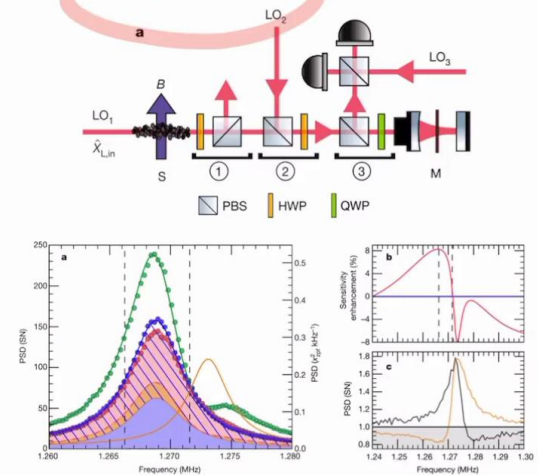


Nature 507, 81 (2014)

Scientific Reports 9, 18173 (2019)

Quantum Backaction Evasion

Spin-Opto-Mechanics



PRL 102, 020501 (2009)

Nature 547, 191 (2017)

Sensing is another big topic and optomechanical signal transduction can help in many ways. Here's an example from magnetic resonance imaging. There are the challenges to read out MRI signals with as little noise and as much amplification as possible. Typically the presence of strong magnetic fields in NMR machine prevent this. The optomechanical solution is to upconvert the MRI signal to the optical domain. The signal can then be analyzed at the end of a long low-loss optical fiber thus moving the receiver electronics away from the coils in high magnetic fields near a scanner. Going to the quantum regime, I just told you about the Standard Quantum Limit when you try to measure the position of a mass using an optical cavity. Well, it turns out if you add another degree of freedom, say, for example, a spin degree of freedom to the optomechanical system, you can circumvent the Standard Quantum Limit. Here the idea is that if you measure position relative to an oscillator with negative mass then this position measurement can in principle be done with arbitrary accuracy. so no backaction disturbs the measurement. Now, this is sometimes called quantum-mechanics free subsystem.

Notes

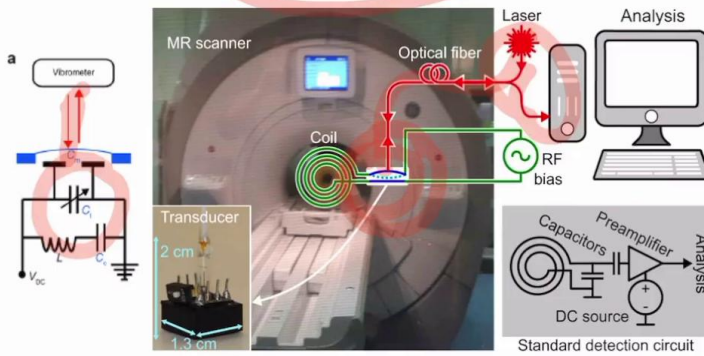
Summary



QUANTUM SENSING

Optomechanical Magnetic Resonance Imaging (MRI)

Electro-Opto-Mechanics

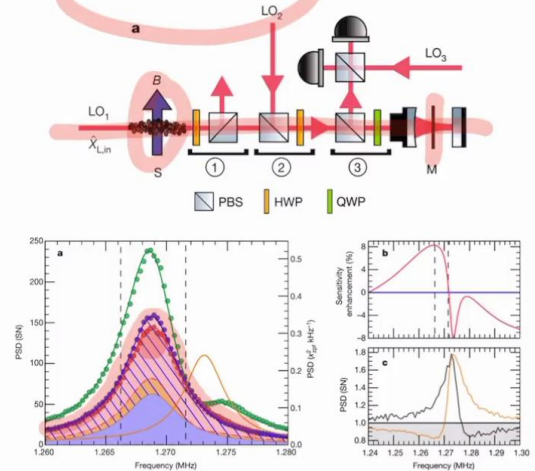


Nature 507, 81 (2014)

Scientific Reports 9, 18173 (2019)

Quantum Backaction Evasion

Spin-Opto-Mechanics



PRL 102, 020501 (2009)

Nature 547, 191 (2017)

In this specific case, the master measure is a micromechanical membrane inside an optical cavity and the negative mass oscillator is actually made of the collective spin degree of freedom of an atomic ensemble sitting in an external magnetic field which allows to energetically invert the spin population and that then realizes negative mass oscillator. Well, the light couples now these two systems with each other and allows also to read out of the relative the degree of freedom between the two. Here you see the results. The blue is the fluctuation of the membrane alone and the red is the backaction reduced measurement. It's a small but visible effect.

Notes

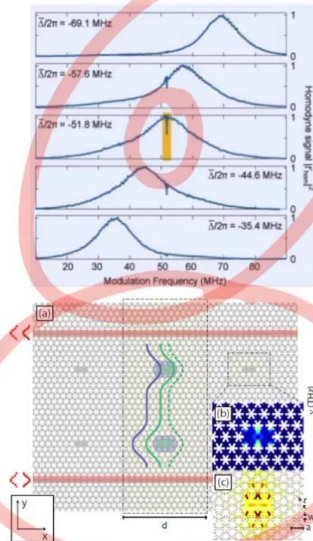
Summary



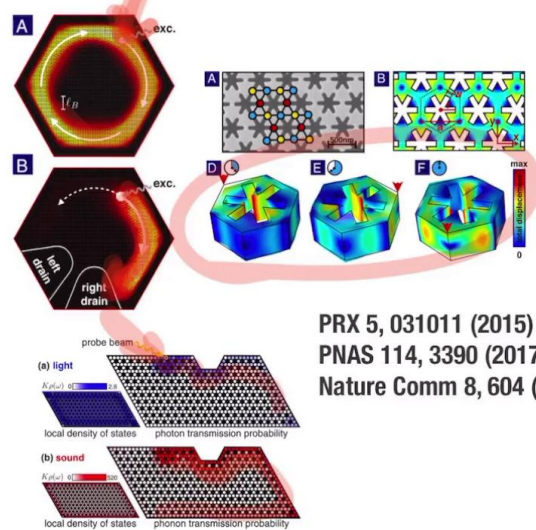
ON-CHIP SIGNAL PROCESSING

Storage of light in 2D-photonic crystal arrays

Optomechanically induced transparency
Science 330, 1520 (2010)
Nature 472, 69 (2011)
NJP 13, 023003 (2011)



Non-reciprocal circuits and topological phases



PRX 5, 031011 (2015)
PNAS 114, 3390 (2017)
Nature Comm 8, 604 (2017)

Another opportunity is full on-chip signal processing. As you can see here, for example, for these cavity transmission functions the optomechanical interactions can strongly modify the dispersion relation of the system which means that we can change the group velocity dramatically which can be used for slowing our storage of light. And in even more complex settings you can think of now storing individual full rear components of an optical pulse in arrays of optomechanical cavities which provides, for example, a full optical memory an quantum memory on a chip. Another application area for arrays are topological states of matter which are particularly robust. For phonons those states can be based on cavity optomechanics and photonic crystals. There are different ways to implement them and in one case, the topological properties are encoded in amplitude and frequency of the drive laser. Here that pumps the optomechanical crystal. And this results in a topologically protected phonon transport even around obstacles and this can be read out via the light. In another case, a specific geometry is used, the so-called snowflake crystal geometry to create pseudomagnetic fields for the sound waves and this implementation does actually not require wavefront engineering when driving the excitation to achieve then a chiral transport here, for example, from the excitation to the drain.

Notes

Summary



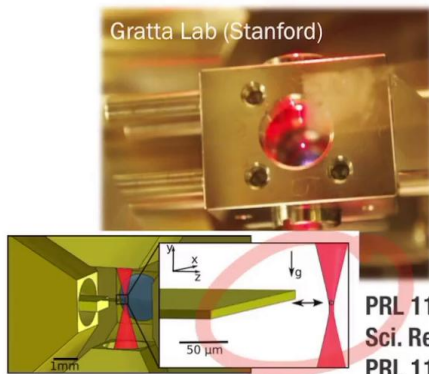
10m 07s

FOUNDATIONS: PRECISION SEARCHES FOR NEW PHYSICS

Low-energy consequences of new scalar fields: additional forces

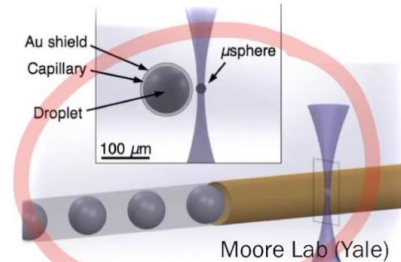
→ optomechanical force sensors

Signatures of Dark Matter and Dark Energy



PRL 113, 251801 (2014)
Sci. Rep. 5, 8058 (2015)
PRL 117, 101101 (2016)
arXiv:2008.0607 (2020)

Gravity at small distances



PRL 105, 101101 (2010)
PRL 122, 071101 (2019)
arXiv:2004.10973 (2020)

Another recent field of relevance for optomechanical systems is searches for new physics. It turns out, for example, that most dark matter candidates also affect the motion of massive solid state objects and hence optomechanical precision sensors allow new tests for these searches. Also scalar fields that may be responsible for dark energy result in additional short-range forces between meta systems. And here's an example where a levitated particle has been brought in close contact to a gold plate in order to measure short-range interactions here. In addition, theories that attempt to unify gravity with the standard model also suggest that gravity may deviate from the Newtonian form so from the one over 'r' potential at micron scale length scales. And several proposals exist so far based on optomechanical sensors to probe gravity at up-to-now unachievable this small distances. So optomechanical sensors certainly cover a unique parameter space for these searches.

Notes

Summary

12m 03s



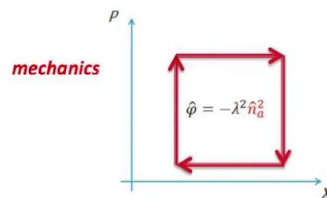
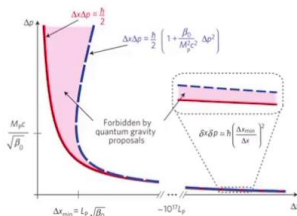
FOUNDATIONS: TESTING QUANTUM GRAVITY

Low-energy consequences of quantum gravity: modified dynamics

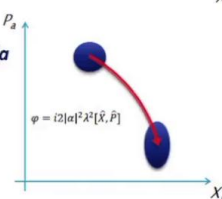
→ optomechanical quantum state control

Planck-scale physics: modified commutators...

Non-local effective field theories...

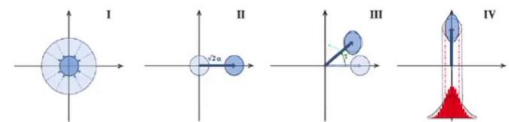


optical ancilla



... generate

- optomechanical geometric phases
- mechanical anharmonicities
- modified ground state energies



... generate time-dependent mechanical squeezing

Nature Physics 8, 393 (2012)

Nature Physics 9, 71 (2013)

Nature Comm. 6, 7503 (2015)

PRL 116, 161303 (2016)

PRD 100, 066020 (2019)

Nature Comm. 11, 3900 (2020)

To push things even more, optomechanical systems have been suggested as test for quantum gravity. To be more precise, as tests for low energy consequences of theories of quantum gravity. Turns out that one of the consequences at low energies can be modified dynamics of solid-state mechanical systems. For example, modified commutators as suggested by some theories of quantum gravity lead, for example, to geometric phases in optomechanical interactions, mechanical anharmonicities or modified ground state energies. All of which can be measured with sufficiently good optomechanical quantum state control. Other theories of quantum gravity such as non-local effective field theories also generate observable consequences such as time-dependent mechanical squeezing. And it is certainly fascinating that optomechanical systems can provide bounds for parameter spaces of quantum theories of gravity in lab-based experiments.

Notes

Summary

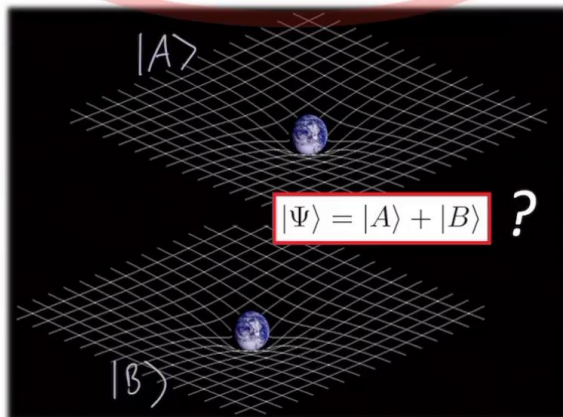


13m 27s

FOUNDATIONS: MACROSCOPIC QUANTUM PHYSICS

Quantum superposition of massive objects: how does a quantum system gravitate?

$$G_{\mu\nu} = 8\pi \langle T_{\mu\nu} \rangle$$



Entangling massive objects via gravity

- requires superposition of space-time metric
- requires quantization of the gravitational field
- may be possible with optomechanical systems

R. Feynman, Chapel Hill (1957)
PRL 119, 240401 (2017)
PRL 119, 240402 (2017)
PRD 98, 126009 (2018)
Phys.Lett.B 792, 64 (2019)

Finally, one of the ultimate challenges is to directly probe effects of the quantum nature of gravity. Up to now we only have experiments that show how a quantum superposition behaves in the presence of gravity. The other way around, of course, is much more interesting. How does gravity behave in the presence of a quantum superposition? One way to probe that is to try to entangle massive objects using a gravitational interaction. Something like that would require superposition of a space-time metric which right now in the current form of Einstein's field equations is not possible but is, of course, the underlying assumptions of all the quantum theories of gravity. Mechanical systems in the quantum regime are uniquely suited for such experiments because they're the only ones to date that combine large mass with high density and hopefully large coherence.

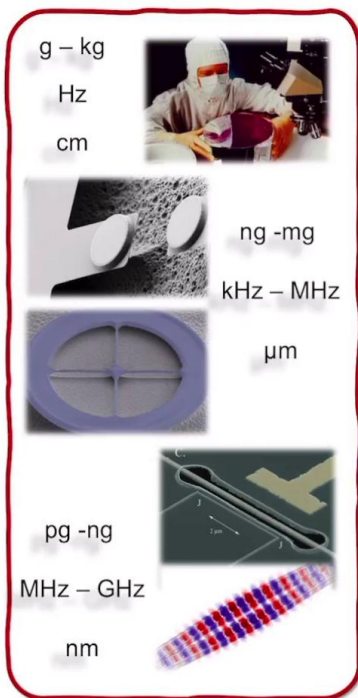
Notes

Summary



14m 40s

SUMMARY



Cavity Quantum Optomechanics

- is a new way to manipulate light and matter on the nano-, micro- and macroscale
- enables **new chip-scale technologies** for quantum transduction, (classical and quantum) signal processing, and complex many-body dynamics
- provides **unprecedented sensing** capabilities
- opens a hitherto **unexplored parameter regime for fundamental physics**: from precision tests of new physics to tests of the gravity-quantum interface

To sum up cavity optomechanics or cavity quantum optomechanics as it's sometimes called is a new way to manipulate light and matter on the nano, micro and macroscale. It enables new chip-scale technologies for quantum transduction, signal processing both in the classical and the quantum domain and complex many-body dynamics. It provides unprecedented sensing capabilities and opens a up-to-now unexplored parameter regime for fundamental physics. We had looked at precision tests of new physics up to completely new experiments at the gravity quantum interface. If this isn't fun, what is?

Notes

Summary



15m 46s