

EPFL

OUTLINE

In this lesson, you will learn about optical forces and the ensuing coupling between optical and mechanical degrees of freedom

- Optical forces in astronomy and laboratory physics
- Radiation pressure from the transfer of linear momentum
- Optical force on an polarizable particle, optical tweezers
- Optical forces on deformable cavities
 - Moving boundary effect
 - Photo-elastic effect
- Photo-thermal coupling

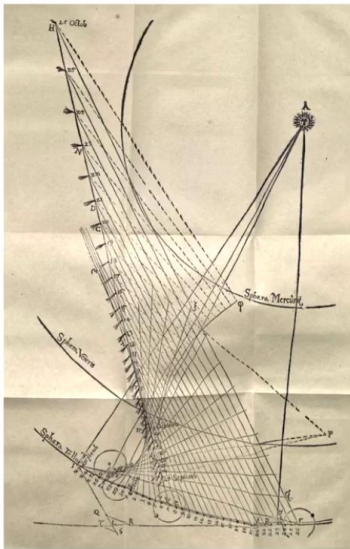
Welcome to this lecture on optical forces. My name is Albert Schliesser. I'm a professor at the Niels Bohr Institute of Copenhagen University. In this lesson, you will learn about optical forces and the ensuing coupling between optical and mechanical degrees of freedom. We will start with a very brief review of optical forces in astronomy and laboratory physics. We will then look at radiation pressure as a form of transfer of linear momentum from light to mechanical objects. We will then discuss optical forces on polarizable particles and the application in optical tweezers. And we will then turn to the canonical optomechanical systems consisting of deformable optical cavities and discuss how optical forces can be described in such a setting. In particular, optical forces related to moving boundaries and the photoelastic effects. And finally, we will discuss photo-thermal coupling between light and motion.

Notes

Summary



HISTORY



Marriott Library, The University of Utah

17th century: astronomy

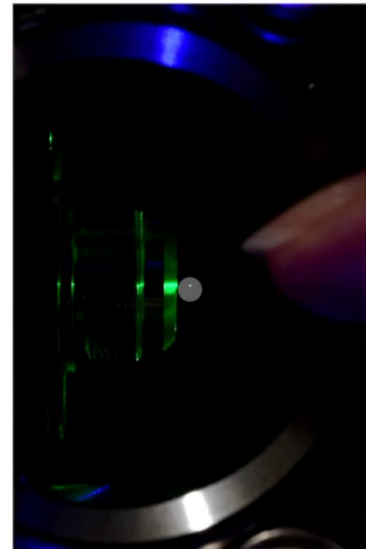
Kepler, "de cometis" (1619)



Science Museum/SSPL, London

19th century: laboratory research

Crooks, Lebedev, Nichols, Hull



Diehl/Reimann, ETH Zurich

20th century: the laser

Chu, Cohen-Tannoudji,
Phillips, Ashkin

Optical forces have long been known. In fact, Kepler already conjectured from his observations of comets that the light exerts a force on the small particles emitted from a comet given that the tail of the comet would always point away from the Sun. But it was only in the 20th century that quantitative research could be undertaken in the laboratory and even though Crooks was probably the first one to make observation of motion induced by irradiation with light, it was only Lebedev in Russia and Nichols and Hull in the U.S. who were first able to quantitatively study this effect with instruments similar to the one shown here in the middle. And a huge step forward in this research could be taken with the advent of the laser that allowed to strongly concentrate light and have coherent light field monochromatic light fields available. This led among others to a host of applications of radiation pressure and optical forces in manipulating the motional state of microscopic particles such as atoms or ions but also manipulating small dielectric objects and also biological objects in the so-called optical tweezer. This is something that was pioneered by Arthur Ashkin. In the picture here you see how it's actually possible with laser light to trap in front of an optical objective, a small dielectric particle and we'll get back to this setting.

Notes

Summary



RADIATION PRESSURE

Linear momentum per photon

$$\vec{p} = \hbar \vec{k}$$

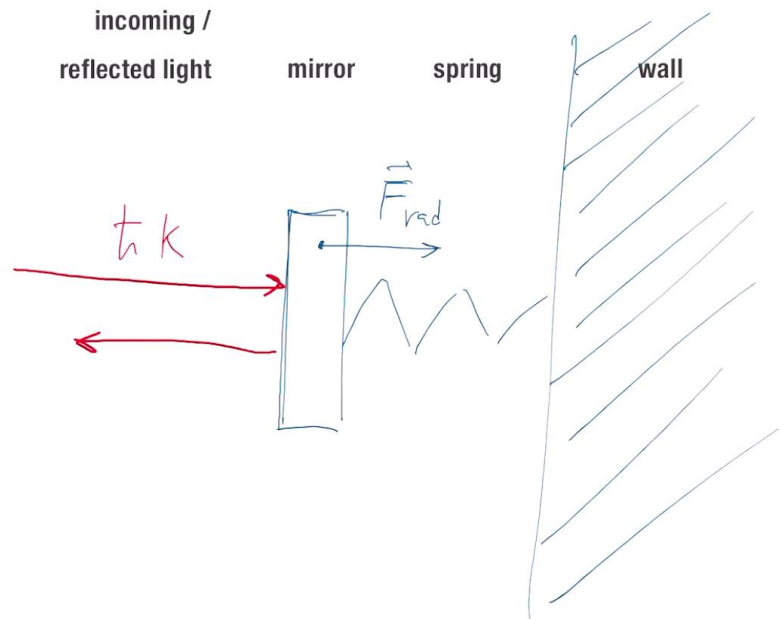
Force (rate of momentum transfer)

$$\vec{F} \equiv \dot{\vec{p}} = \frac{P}{\hbar \omega} \cdot 2\hbar \vec{k}$$

$$F = 2P/c$$

Laser power needed
to lift a coin against gravity

$$P \sim mgc \sim \mathcal{O}(10 \text{ MW})$$



Here we want to discuss how we can quantify these forces and the ensuing coupling between light and motion. And it turns out that using the particle picture for light gives us a quite straightforward way to do this. In the simple case where we just reflect a light field off a mirror and we want to know what is the force that this light field exerts on this mirror. And to do that, we need to know that the linear momentum of a single photon is given simply by the Planck constant times the wave vector 'k'. And then we can immediately calculate the force which is just the rate of momentum transfer by obtaining the rate of reflection events. This is the optical power divided by the energy of one photon and multiplying it with the momentum transfer which is two times the momentum of the photon because it basically changes its direction by a hundred degrees, 'k' becomes minus 'k'. And knowing the dispersion relation of light, this tells us that the magnitude of this force is just given by two times the optical power divided by the speed of light. So is this a small force? Well, or a large force, well, it depends certainly when it comes to macroscopic objects so let's imagine, for example, a coin that weighs a few grams.

Notes

Summary



RADIATION PRESSURE

Linear momentum per photon

$$\vec{p} = \hbar \vec{k}$$

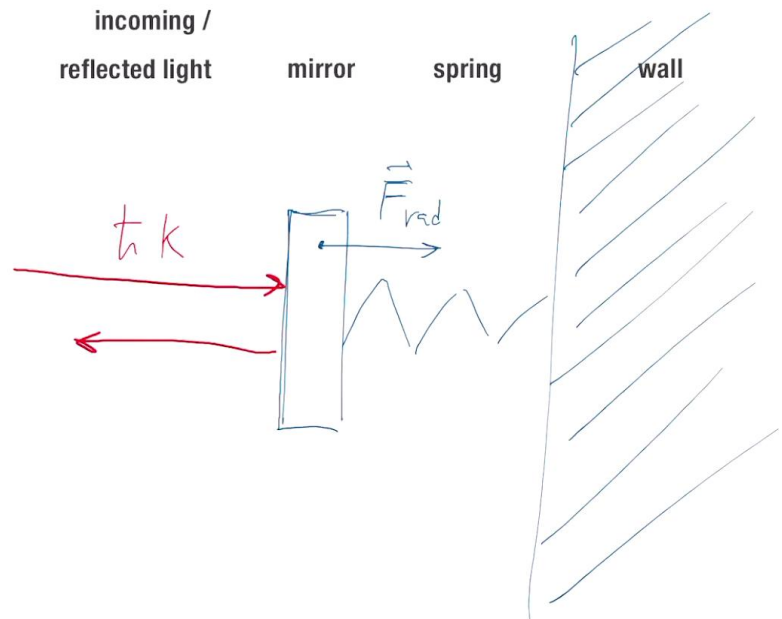
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Laser power needed
to lift a coin against gravity

$$P \sim mgc \sim \mathcal{O}(10 \text{ MW})$$



If you would want to lift such a coin against gravity, we would need an optical power on the order of ten megawatts so this is more laser pointers than you can buy so this is something very very large. Nonetheless, optical forces appear in a number of laboratory experiments and here's just a few of them.

Notes

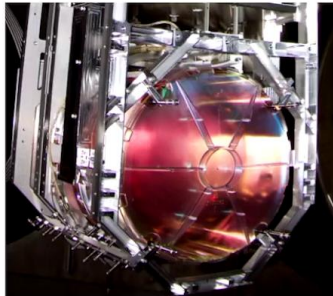
Summary

4m 57s



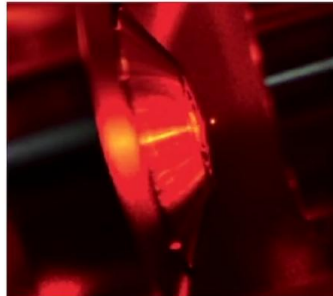
OPTICAL FORCES IN COMPLEX GEOMETRIES

Interferometer mirror



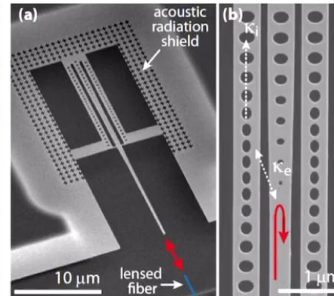
Caltech/MIT/LIGO Lab

Trapped nanoparticle



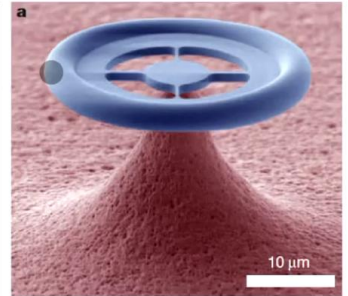
Jain *et al.*, PRL **116**, 243601 (2016)

Photonic crystal



Meenehan, PRA **90**, 011803 (2014)

Microtoroid



Verhagen *et al.*, Nature **482**, 65 (2012)

Rigid bodies - change in center of gravity

Deformable bodies - change in shape

How to calculate optical forces / light-motion interaction in these geometries?

Indeed they appear even for large objects like this mirror of a gravitational wave observatory. This is a laser interferometer with mirrors that weigh many many kilograms and it's here where we just reflect a laser light directly of this mirror that the consideration we just made would apply relatively straightforwardly if we want to know the optical force. Things get a lot more complicated when we would like to know what is, for example, the optical force that tightly focused laser beam, again this is an objective here, exerts on a particle here trapped in vacuum? And possibly even more complicated is the question, what happens if we trap light in such a patent dielectric structure? So if we trap light around these holes here, how does this exert a force that could possibly deform this piece of dielectric here, in this of case silicon, or if we manage to have light circulating around such a toroid here, to which extent will this actually increase dilate this the radius of this torus? So we could actually classify already these situations into two different classes.

Notes

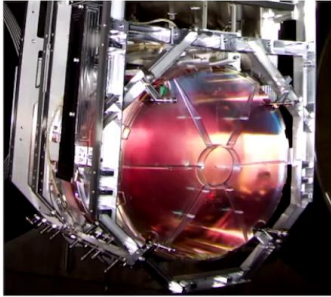
Summary



5m 25s

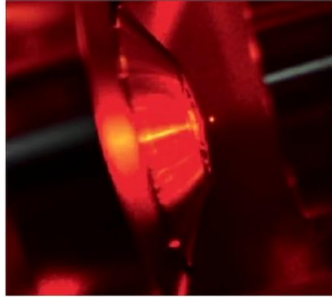
OPTICAL FORCES IN COMPLEX GEOMETRIES

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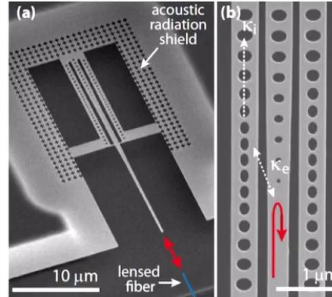
Caltech/MIT/LIGO Lab

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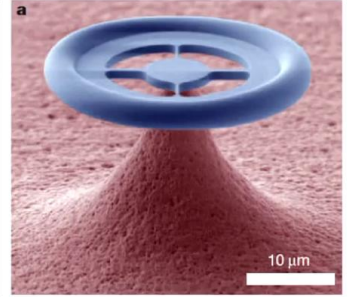
Jain *et al.*, PRL **116**, 243601 (2016)

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Rigid bodies - change in center of gravity

Deformable bodies - change in shape

How to calculate optical forces / light-motion interaction in these geometries?

On the one hand for this mirror and for this small particle here we would be interested in how the center of mass motion of some object like this large mirror or this small particle is moving under the effect of the optical force so this would be a rigid body and here we would be interested in how light actually deforms these objects. And it turns out that it will be convenient to actually use different languages different formalisms to describe the light meta or light motion coupling in these settings.

Notes

Summary



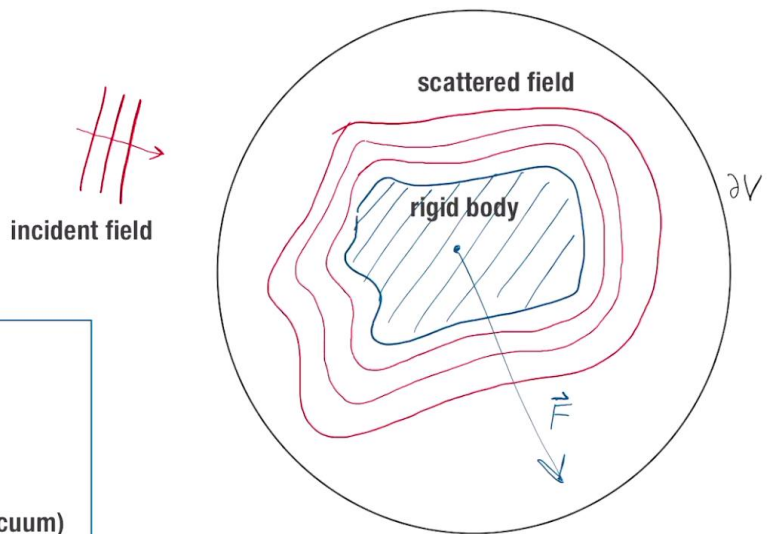
6m 54s

FORCES IN CLASSICAL ELECTRODYNAMICS

Force on a charge (distribution)

$$\vec{F} = q (\vec{E} + \vec{v} \times \vec{B})$$

$$\vec{F} = \int (\rho \vec{E} + \vec{j} \times \vec{B}) dV$$



Time-averaged force on a rigid body

$$\langle \vec{F} \rangle = \oint_{\partial V} \langle \vec{T} \rangle \cdot \hat{n} dA$$

with components of the Maxwell stress tensor (in vacuum)

$$T_{ij} = \epsilon_0 E_i E_j + \mu_0 H_i H_j - \frac{1}{2} (\epsilon_0 \vec{E}^2 + \mu_0 \vec{H}^2) \delta_{ij}$$

Most generally, we would actually resort to classical electrodynamics so we could use basically Maxwell's equations and they in principle tell us what the force would be on a charge that is possibly moving so if we have, in fact, a charge distribution described by ρ here and a current density described by \vec{j} here, we can actually calculate what the overall force is by basically integrating up all the contributions throughout the volume of a body. And now since Maxwell's equations give us relations between these fields and their sources ρ and \vec{j} , we can actually recast this force as the time averaged integral over something that is known as the Maxwell stress tensor and we can in turn recast this expression as, in fact, a surface integral over the boundary of some volume and this boundary being ∂V here. And we basically take this Maxwell stress tensor, multiply it with the surface normal and then evaluate the force and the components of the Maxwell stress tensor are given by this expression. So if we do know exactly what the electric and magnetic fields are throughout such a surface, we can actually calculate what is the force exerted on a body contained inside this volume.

Notes

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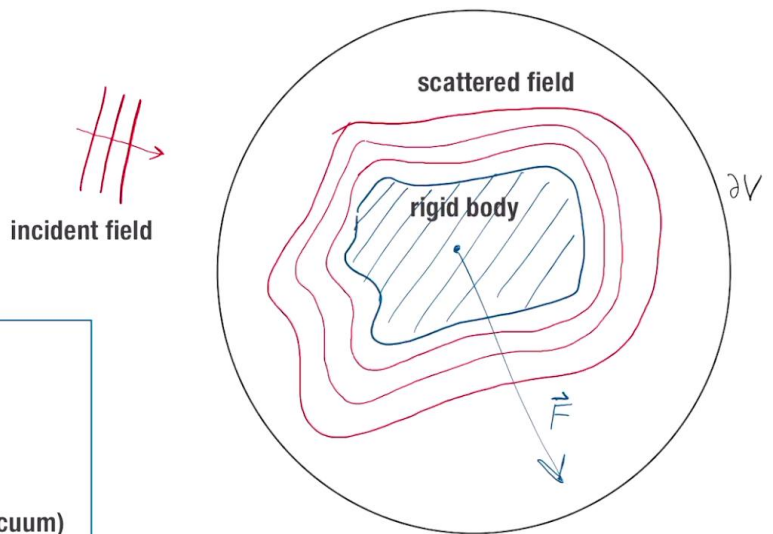
7m 34s

FORCES IN CLASSICAL ELECTRODYNAMICS

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Now these fields that we have to plug in into this expression need to be the fields that take into account the fact that this body is actually scattering the light and this in itself can be something rather complicated.

Notes

Summary



OPTICAL FORCES ON AN POLARIZABLE PARTICLE

For a polarizable (point) particle:

$$\langle \vec{F} \rangle = \frac{\alpha'}{4} \vec{\nabla} E_0^2 + \frac{\alpha''}{2} E_0^2 \vec{k}$$

gradient force /
dipole force

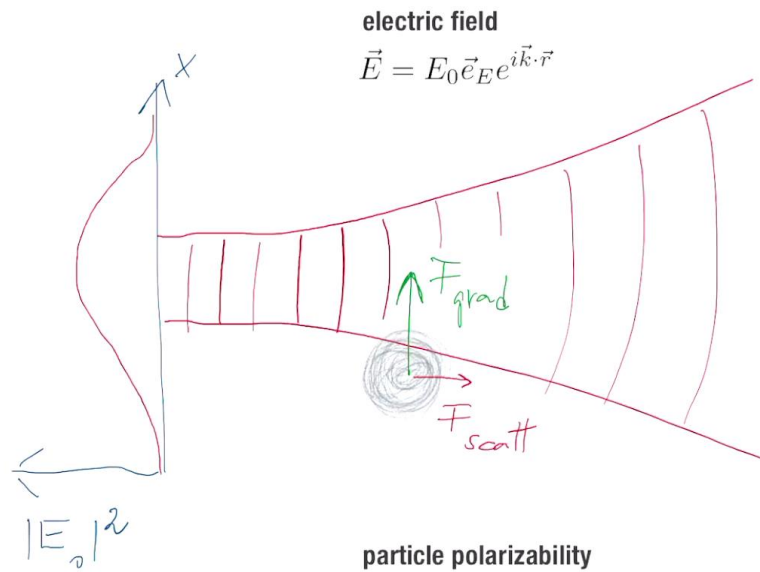
reactive
conservative

Follows
intensity
gradients

scattering force

dissipative

Along beam
direction



So we're looking for some simplified expressions here and it is indeed possible to get such expressions in the case where the body the rigid body that we're dealing with is a small particle which we can describe simply by a polarizability α which has a real part and an imaginary part. The real part effectively referring to the polarization that is in phase with the electric field and the imaginary part to the polarization that is out of phase with the electric field. So this term here would refer to a dissipative process where basically the particle absorbs the light and potentially re-emits it whereas here this is really a conservative term where we just have an in-phase oscillation of the dipole with the electric field. And indeed these two contributions give rise to rather different behavior. In particular, this first term here is basically a conservative force where the potential is just given by basically the optical intensity. So the particle will just follow the gradient of this optical intensity and therefore, this force here is called the gradient force and sometimes also the dipole force.

Notes

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OPTICAL FORCES ON AN POLARIZABLE PARTICLE

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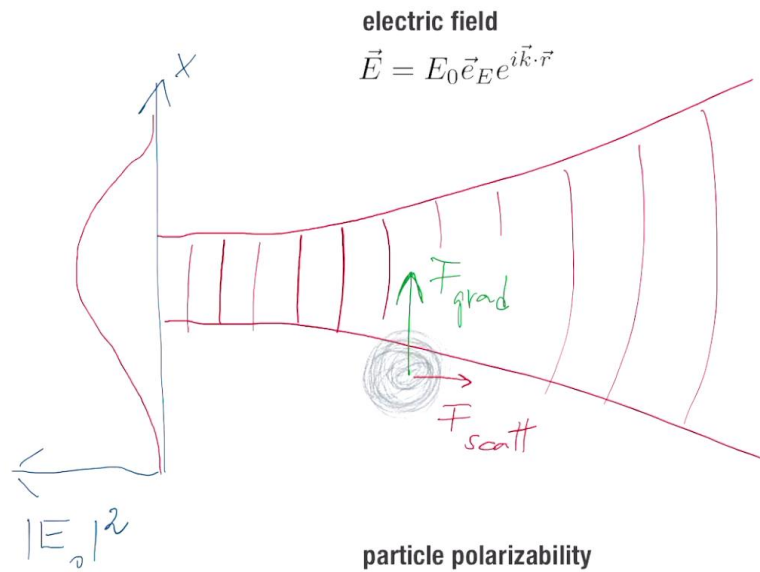
scattering force

reactive
conservative

dissipative

Follows
intensity
gradients

Along beam
direction



particle polarizability

$$\alpha = \alpha' + i\alpha''$$

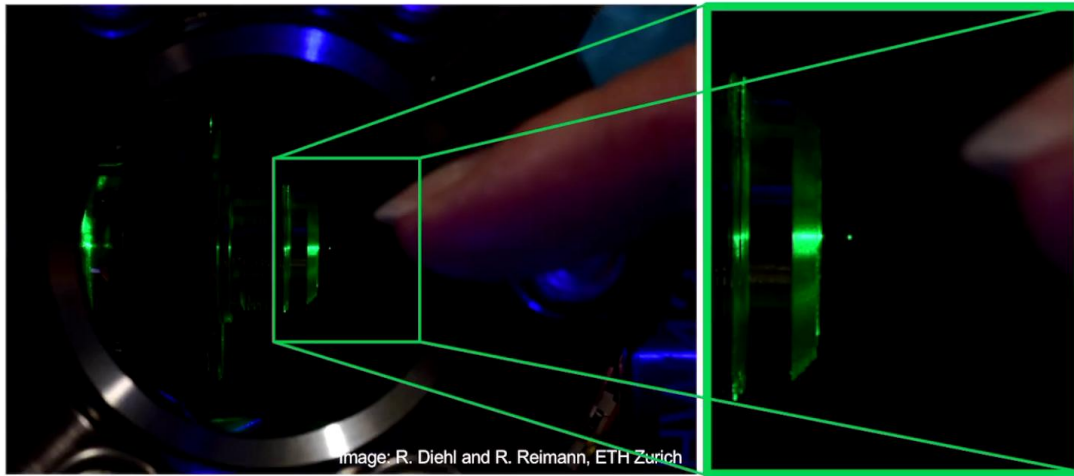
So if I'm looking at a tightly focused laser beam as I've indicated here with these red lines, what this particle this polarizable particle would do is it would seek the maximum of the optical intensity. So the gradient force would point here towards the focus of this laser field. And on the other hand, we have this second term here the scattering force, where the particle really absorbs the light and thereby, basically also taking over the linear momentum of the photons. This is a dissipative process and this points in this example that I've shown here along the beam direction so if the laser would come from the left here then this scattering force would push this polarizable particle here in the direction of the laser beam. And the relative contributions of these two depends among other things on the ratio of the real and imaginary part of the polarizability, which in the case of a atom strongly depends on the detuning of this laser field with respect to the transition frequency of the atom so if you're close to resonance then this scattering force will become larger. If you're far off resonance, the dipole force can be larger.

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OPTICAL TWEEZERS



A tightly focused laser beam forms an optical tweezer capable of stable trapping of dielectric particles, biological specimen, atoms, molecules, ... in water, air, vacuum, ...
(Art Ashkin, Nobel Prize in Physics 2018)

Now as I have already indicated, the dipole and the dipole force can be used in so-called optical tweezers by making a very tightly focused laser beams. Laser beam I can actually trap particles that are polarizable in the laser focus and that is possible not only for atoms and molecules but also for dielectrical particles or biological specimen, such as cells or viruses in various environments including a vacuum, water and air and only recently Art Ashkin actually received the Nobel Prize in Physics for pioneering these techniques already a many decades ago because it really led to many applications among others in Biophysics. But the optical tweezers are actually also used in optomechanics. You see this image here is actually from the group of Lukas Novotny in ETH Zurich where they are looking at optomechanics with exactly such trapped dielectric particles.

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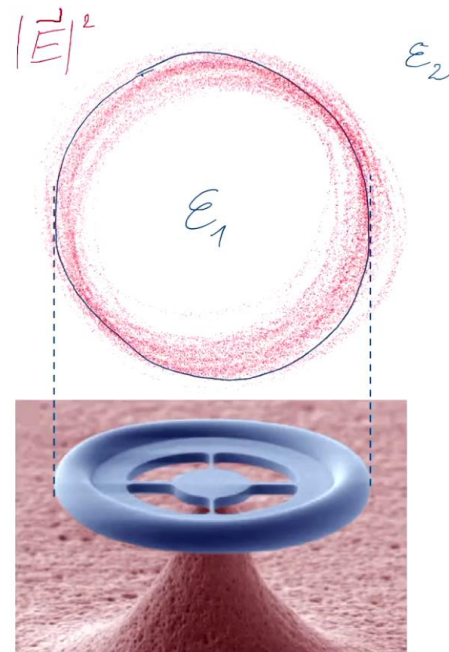
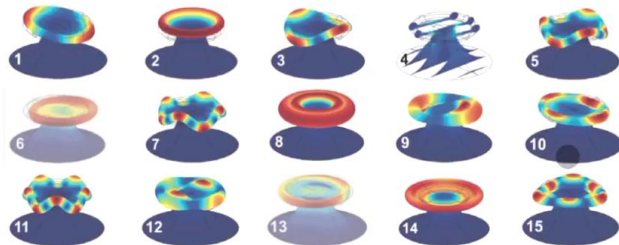


13m 10s

EFFECTIVE FORCES IN DEFORMABLE CAVITIES

An optical cavity confines photons ...

... and simultaneously supports mechanical resonances



Let us turn our attention now to deformable objects where we are interested in how optical forces deform a body. For this to happen, we typically confine the light into a cavity so this is really the setting now of cavity optomechanics where we trap the light in a resonator which has among other things the important effect that it enhances the optical power that is circulating or the optical energy trapped in a small volume of space. So in the example that I want to discuss here we have a toroid made from glass. This is this blue-colored object here which if you imagine looking at it from the top. Around its rim actually confines an optical field whose 'E' field shall be indicated here with this shade of red. And so as far as the sort of dielectrics are concerned, we have the situation that's sort of inside this rim here so in this blue area we have one dielectric constant and outside we have another dielectric constant that would be the one of matching in this case. So the optical cavity confines photons and this structure actually simultaneously supports mechanical resonances. I've shown here some displacement patterns of these mechanical resonances. Depending on their frequency they look they assume, you know, different shapes. So you can think of this similarly to say, the various modes of excitation of a violin string, for example.

Notes

Summary



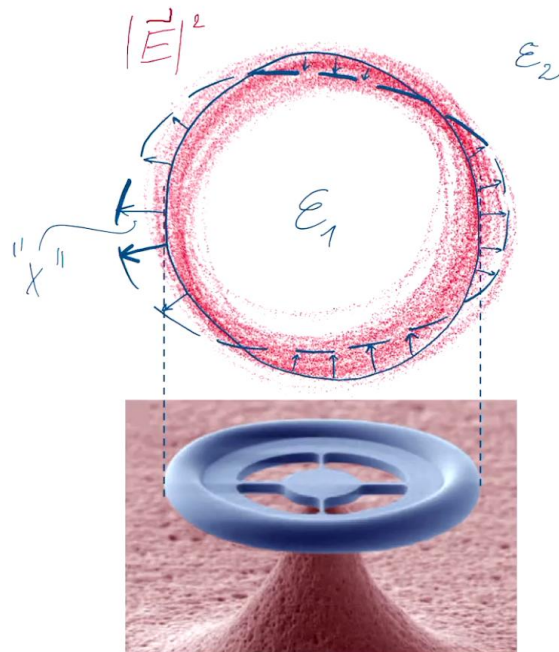
14m 21s

FREQUENCY PULL PARAMETER

Cavity deformation changes energy of confined photons.

Force is the derivative of optical energy with respect to deformation amplitude:

$$F = -\frac{dE}{dx}$$



Now in this example, we will be focusing on a mechanical mode that looks approximately like the one with a number ten here and we will be asking ourselves how does the optical mode trapped in this ring interact with the motion as described by this mode here? So in fact, a very convenient way to describe this interaction is to consider that if the cavity deforms as prescribed by the shape of this mode here of this mechanical mode here, this will change the energy of the photons confined in the optical resonator and the force, therefore, that the light exerts on this kind of mode is given simply by the change of the optical energy as a function of the mode displacement. Okay, so I pick some particular amplitude here of this complex mechanical mode shape, I give it the name 'X' and I look at how does the optical energy change when this 'X' assumes a certain value and then the force that the light exerts on the mechanical mode is simply given by the derivative of the energy with respect to the displacement 'X'. All right, so the force is the derivative of the optical energy with respect to the deformation amplitude.

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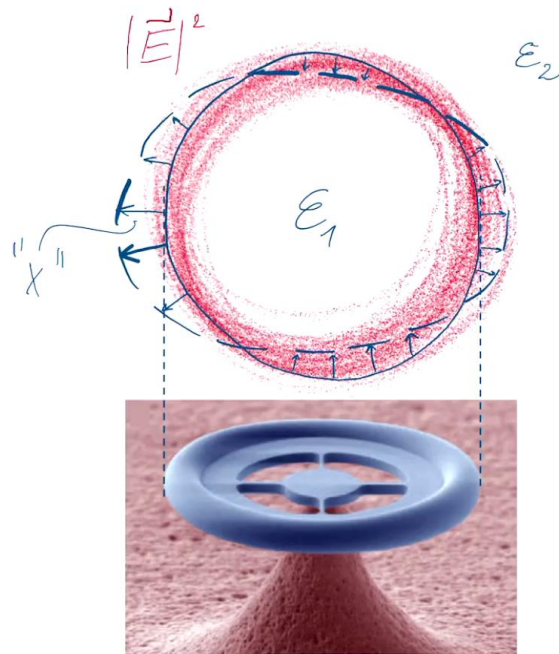
16m 19s

PERTURBATIVE APPROACH

Force on a deformable cavity: $F = -n\hbar G$

Perturbation theory for cavity frequency yields:

$$G = \frac{d\omega_c}{dx} = -\omega_c \cdot \frac{\int \vec{E}^* \cdot \frac{d\epsilon}{dx} \cdot \vec{E} dV}{2 \int \epsilon |\vec{E}|^2 dV}$$



And I can do this now at the level of a single photon by just saying I know that each and every photon has the energy $\hbar\omega$, where ω is the resonance frequency of this optical cavity and then I just multiply with the number of photons that I have stored in the optical mode. What this gives me is it gives me the force in terms of a parameter that only depends on the structure that I have at hand here and I decouple that from the amount of light that is actually stored in the system. So this is something that I can in principle calculate by only knowing what this structure looks like without knowing how much laser light is sent into this cavity. So this parameter 'G' in optomechanics goes by the name of the frequency pull parameter which is quite clear from looking at the definition. It denotes the frequency shift of the optical mode as a function of displacement of the mechanical mode. So this parameter basically quantifies what we call the parametric coupling between optics and mechanics namely, how the mechanical amplitude as a parameter changes the resonance frequency of the optical cavity. Now how can we calculate this frequency pull parameter? Turns out we can do a perturbation theory.

Notes

Summary



17m 58s

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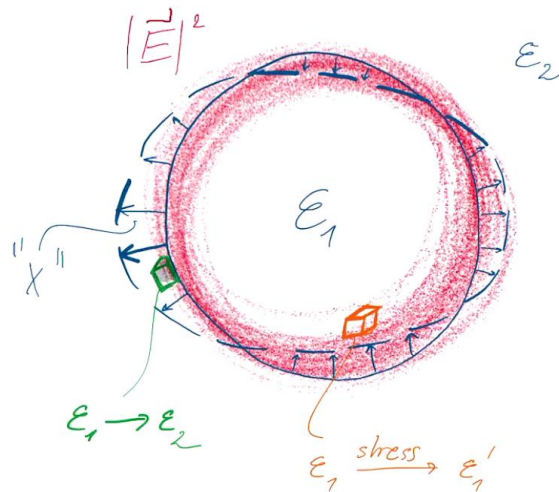
$$G = \frac{d\omega_c}{dx} = -\omega_c \cdot \frac{\int \vec{E}^* \cdot \frac{d\epsilon}{dx} \cdot \vec{E} dV}{2 \int \epsilon |\vec{E}|^2 dV}$$

Two contributions:

1) moving boundaries*

2) photo-elastic effect (stress-optical effect, electrostriction)

Can be of comparable magnitude (and opposite sign)



*Johnson, Ibanescu, Skorobogatiy, Weisberg, Joannopoulos, Fink, PRE **65**, 066611 (2002)

We can, in fact, consider the solution or we can consider the problem of what the optical mode looks like, an eigenvalue problem and we can sort of consider the deformation that we have here a small perturbation and then apply a perturbation theory which will actually give us an expression of this kind here. What we have in the numerator is basically the change in the dielectric energy. So the energy stored in the optical mode as it interacts with the dielectric normalized to the total stored optical energy. There's a factor of two here because we also of course, store energy in the magnetic field associated with the light. And if we think about this situation that we were discussing here, in fact, there are two contributions to how the dielectric constant here changes when I'm exciting the mode so when I'm varying this parameter 'X' here which I've indicated here with two different colors. On the one hand, for example for this volume element here, as the boundary displaces the dielectric constant goes from 'E2' to 'E1'.

Notes

Summary



PERTURBATIVE APPROACH

Force on a deformable cavity: $F = -n\hbar G$

Perturbation theory for cavity frequency yields:

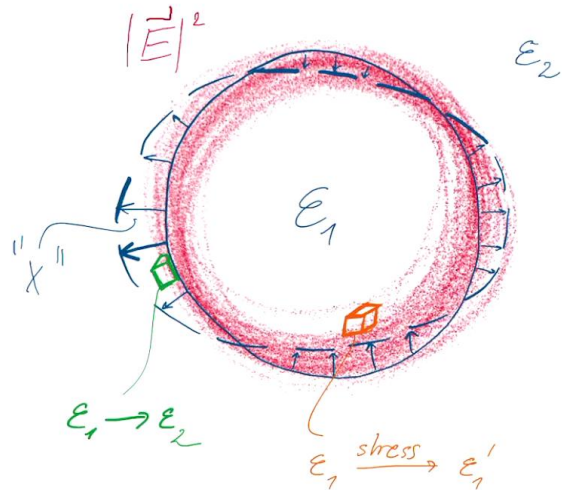
$$G = \frac{d\omega_c}{dx} = -\omega_c \cdot \frac{\int \vec{E}^* \cdot \frac{d\epsilon}{dx} \cdot \vec{E} dV}{2 \int \epsilon |\vec{E}|^2 dV}$$

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It should be inverted from 'E2' to 'E1' from epsilon two to epsilon one which will, therefore, change the energy up here whereas for a volume element here inside the body, it is possible and in fact, observed that given the fact that this material here deforms, I have what is called a stress in the material and a material under stress will in general change its dielectric function or you could also say, its refractive index. So we actually will have that epsilon one goes to some other epsilon one prime. And this is referred to as the photoelastic effect or sometimes actually also the stress optical effect or electrostriction depending on the context but the physics is basically the same. So again what we do is we basically evaluate at each point in space by how much this dielectric constant here changes. We weight this with the unperturbed electric fields or actually electric sort of optical intensity and we normalize it to the total energy stored in the optical mode. There are some subtleties of exactly how these integrals should be evaluated which we're not going to discuss but they are discussed, for example, in this paper here.

Notes

Summary

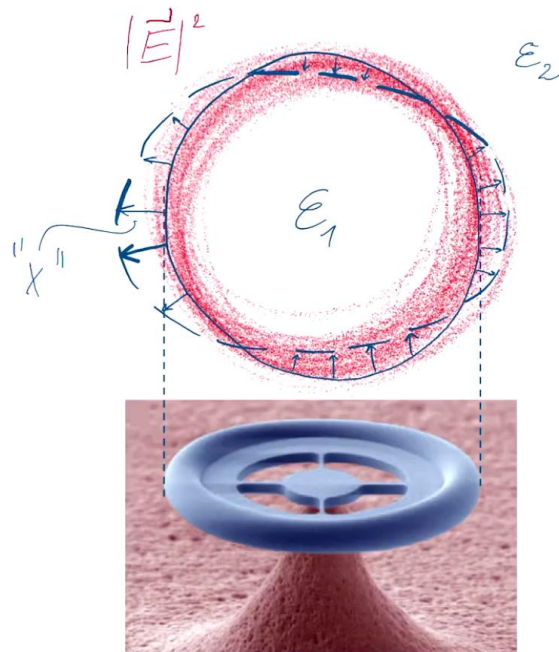


21m 13s

VACUUM OPTOMECHANICAL COUPLING RATE

Definition of mechanical mode amplitude x is ambiguous,
and so is that of the frequency pulling parameter G .

Therefore, normalize to vacuum fluctuations and introduce
the vacuum optomechanical coupling rate $g_0 = x_{\text{zpf}} G$



Now importantly actually these two contributions to moving boundary and the photoelastic contributions can be of comparable magnitude and sometimes they are also of opposite sign and then it really has to be carefully evaluated typically using finite element simulations which can give us these field distributions 'E' here. Now, another caveat that we have to consider is that the definition of the mechanical mode amplitude 'X' is in principle ambiguous. I could also have chosen to call the displacement of the boundary over here 'X' and then, of course, the frequency pull parameter will be different and so will be the force according to the definition that we have used. And that is correct but of course, we want at the end of the day the same physics to emerge and we also want to be able to intercompare actually different systems and a way that to do this which actually anticipates already the description at the quantum level of the optomechanical coupling is to normalize the frequency pull parameter by the zero point motion of the particular mechanical mode. So I'm multiplying the frequency shift that I have per displacement 'X' by the zero point motion, which will then rescale in the same way.

Notes

Summary

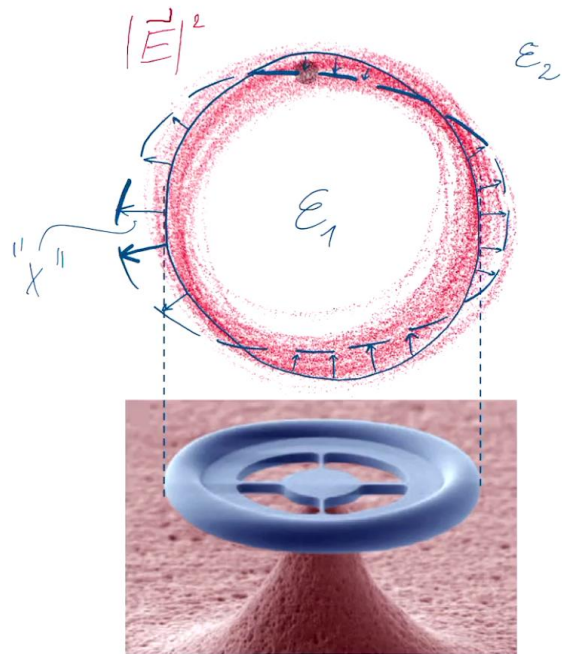


22m 50s

VACUUM OPTOMECHANICAL COUPLING RATE

Definition of mechanical mode amplitude x is ambiguous,
and so is that of the frequency pulling parameter G .

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the vacuum optomechanical coupling rate $g_0 = x_{\text{zpf}} G$



Right. So if I call this thing 'X' here then, you know, if this mechanical mode is displaced by one vacuum unit then it will be displaced by a larger vector here then it will be here and that will basically compensate for the fact that with this definition of 'X', 'G' may be smaller and with this definition of 'X', 'G' may be larger.

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Summary

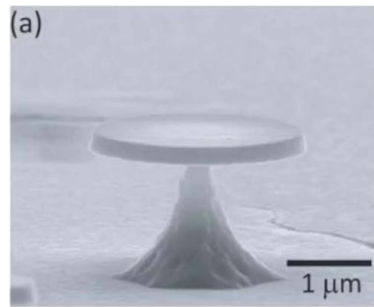


24m 36s

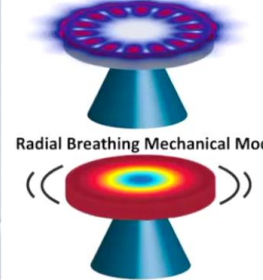
VACUUM OPTOMECHANICAL COUPLING RATE

Example 1:

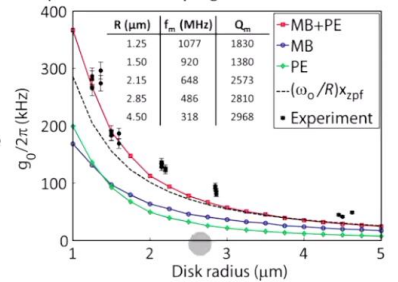
GaAs microdisk



Whispering Gallery Optical Mode

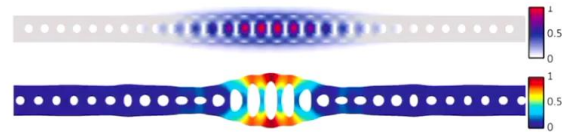
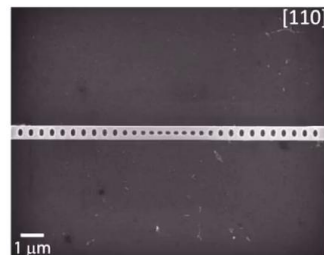


Optomechanical coupling rate in GaAs microdisks



Example 2:

GaAs optomechanical crystal



Material	E [100] (GPa)	$\Omega_m/2\pi$ (GHz)	$g_{0,MB}/2\pi$ (kHz)	$g_{0,PE}/2\pi$ (kHz)
GaAs (circular)	85.9	2.31	-42	563

Balram, Davanco, Lim, Song, Srinivasan, Optica 1, 2334 (2014)

And to give an example here, this is from a paper from Kartik Srinivasan group. We can calculate for a small disk of the material gallium arsenide what these coupling rates are. So indeed this disk, it's a very generic setting of optomechanics supports. An optical mode referred to as a whispering gallery mode where the light basically orbits around the rim here and it also supports a mechanical mode which is a periodic change of the size of the radius of this disk. And you see then here as a function of the radius of the disk the moving boundary part given in blue and the photoelastic part given in green and you see that they both are actually of comparable magnitude so they certainly both have to be taken into account to describe the optomechanical coupling correctly. Which is indeed what you can do by adding them up and you see that the data actually line up with this theory very well. And on the other hand, even in such a complex geometry as this so-called optomechanical crystal which again confines both an optical mode shown here in this upper panel and a mechanical mode shown here as a very exaggerated deformation in the lower panel.

Notes

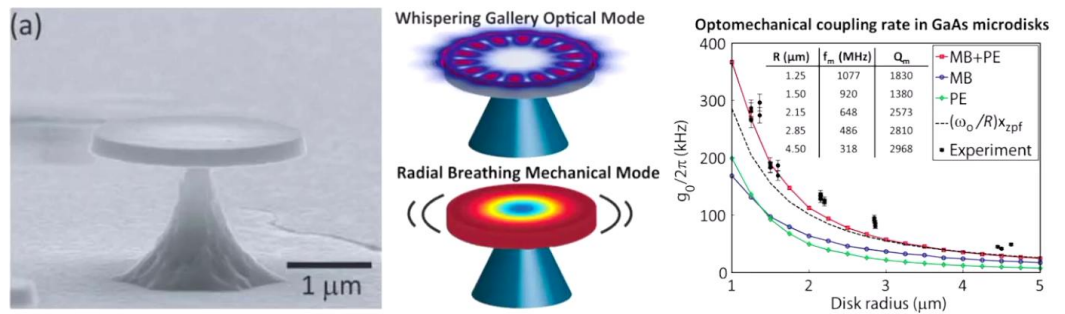
Summary



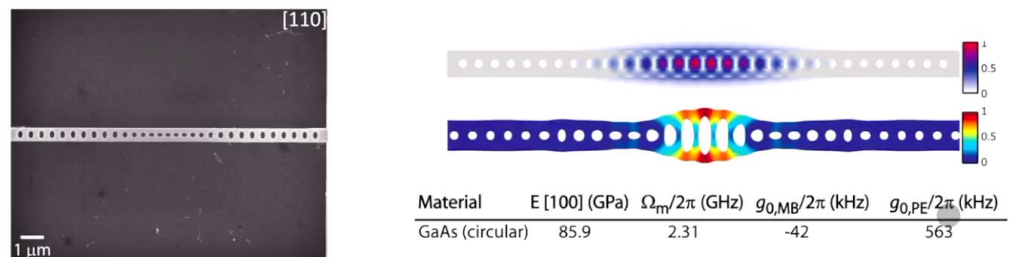
25m 03s

VACUUM OPTOMECHANICAL COUPLING RATE

Example 1:
GaAs microdisk



Example 2:
GaAs optomechanical crystal



Balram, Davanco, Lim, Song, Srinivasan, Optica 1, 2334 (2014)

Even in this complex geometry, I can, in fact, quantify the optomechanical coupling simply by two frequencies which are in this case actually of opposite sign for the moving boundary and the photoelastic part and you see in this case the photoelastic part is actually bigger by a large margin.

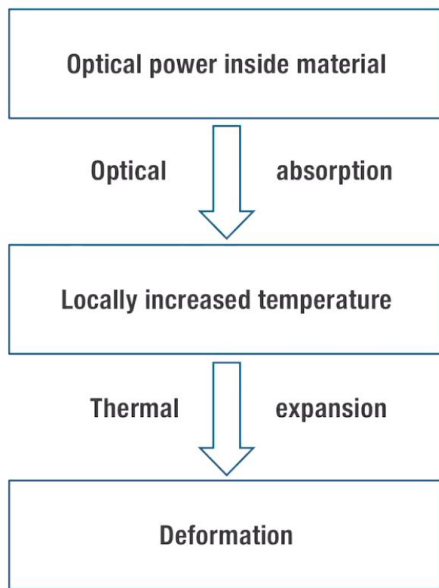
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Summary

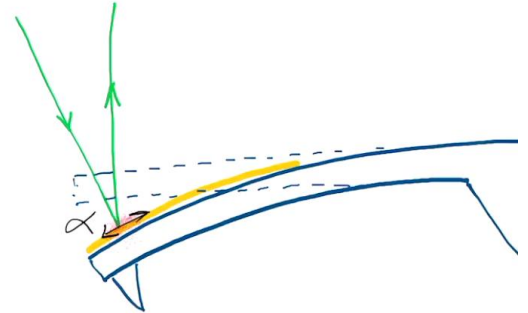
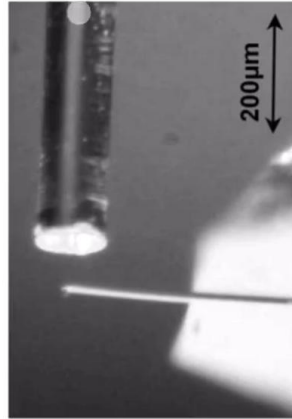


26m 42s

PHOTO-THERMAL COUPLING



Dissipative process that often competes with radiation pressure effects



Metzger, Karrai, Nature **432**, 1002 (2004)
Metzger, Favero, Ortlieb, Karrai, PRB **78**, 035309 (2008)

And finally, I want to mention that in many experiments, in many micro and nano systems another important effect is at play that can be cast also as effectively a force but it's rather different in nature compared to what we have just discussed which is essentially a momentum transfer from light to to meta. So in what is referred to as photothermal coupling, in fact, the material responds because part of the optical power that is hosted in the material is absorbed. Which leads to a locally increased temperature and the material responds to this locally increased temperature which may be different in different places with thermal expansion which then in turn leads to deformation. So a setting where this was observed early on and in a quite dramatic manner is if you reflect off a thin cantilever that has a thin metal coating, let's say, this is gold here on top. If you use an optical fiber here to reflect a laser beam from this cantilever then a significant fraction of the laser light gets absorbed and leads to an expansion of these materials and then in this case, for example, if the expansion of one of the layers is much stronger than the other layer then this will lead to a bending.

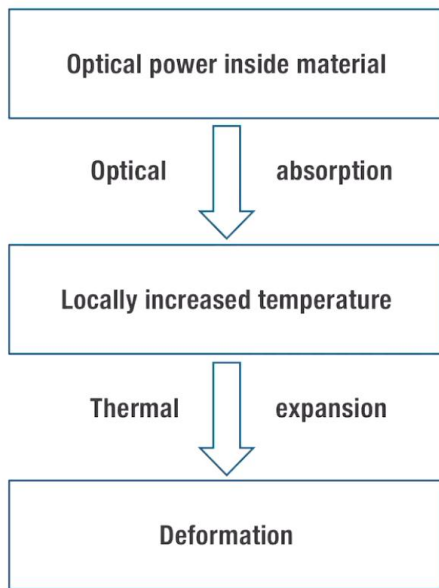
Notes

Summary

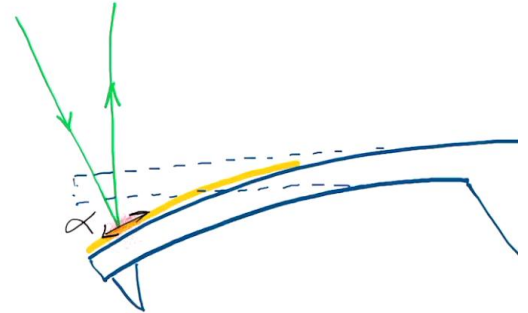
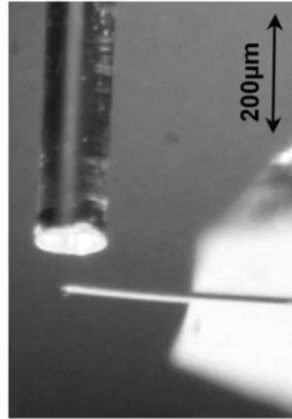


27m 07s

PHOTO-THERMAL COUPLING



Dissipative process that often competes with radiation pressure effects



Metzger, Karrai, Nature **432**, 1002 (2004)
Metzger, Favero, Ortlieb, Karrai, PRB **78**, 035309 (2008)

So to a response in form of a deformation to the optical field which is effectively also a force but it's actually a dissipative process that actually often competes with radiation pressure effects.

Notes

Summary



28m 52s

SUMMARY

- **Optical forces occur in a multitude of settings, and can become prominent in particular when light is**
 - resonantly enhanced in a cavity
 - confined to micro- and nanoscale structures
- **Several physical mechanisms lead to optical forces, which sometimes compete**
- **Different descriptions for the effect of light on motion are available**
 - Forces on rigid bodies: radiation pressure, scattering and dipole force
 - Parametric coupling between optical and mechanical resonances: moving boundary effect, photo-elastic effect

Okay. To summarize optical forces as we have seen here occur in a multitude of settings but they become particularly prominent when light is resonantly enhanced in a cavity so that it reaches sufficiently high powers and when it is confined to micro and nanoscale structures. Several physical mechanisms can lead to optical forces. For example, the effect of a moving boundary but also photoelastic effects or the photothermal effects mentioned at the end and sometimes these effects also compete. And finally, we have different descriptions available for the coupling of light and motion. And we have talked about how to calculate the forces acting on rigid bodies in simple geometries. For example, as radiation pressure or as the scattering and the dipole force on small polarizable particles. And finally, we have discussed how to translate forces to a parametric coupling between optical and mechanical resonances and discuss two effects in particular, namely, the moving boundary and the photoelastic effects.

Notes

Summary



29m 16s