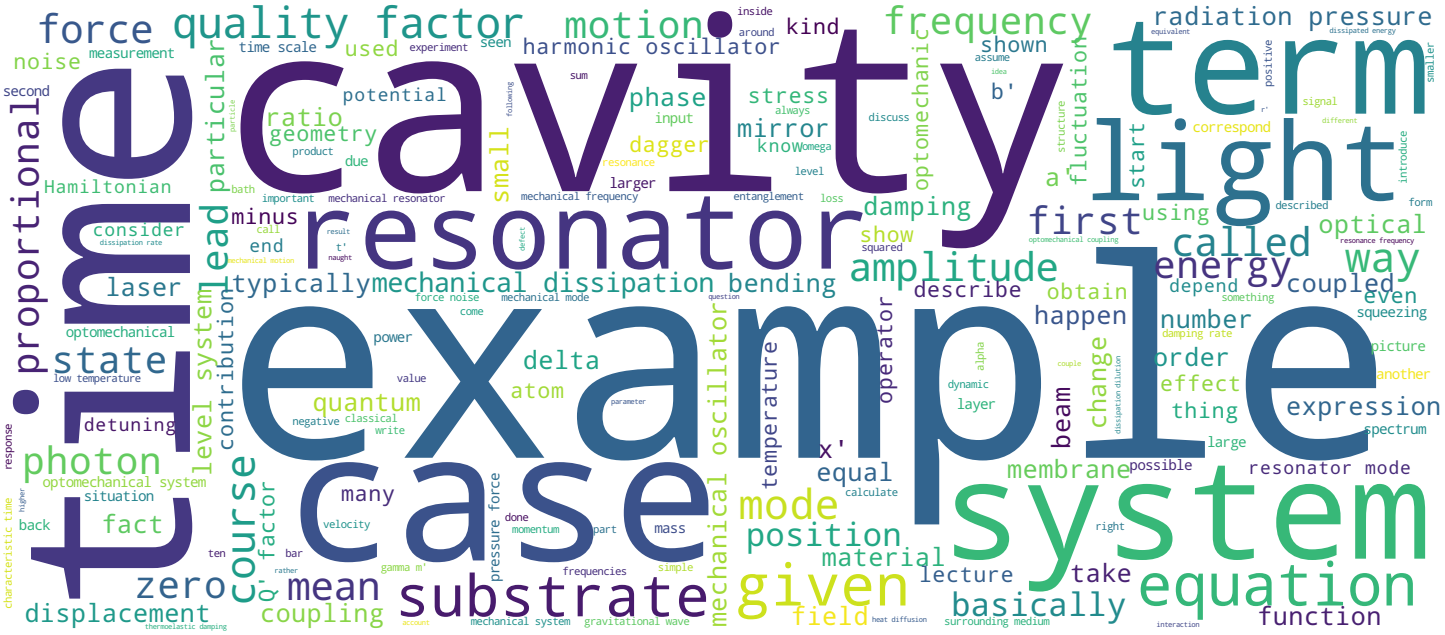
MECHANICAL DISSIPATION

Cavity Quantum Optomechanics

Albert Schliesser
Niels Bohr Institute &
Copenhagen University

UNIVERSITY OF COPENHAGEN



Search MOOC

Video

EPFL

OUTLINE

In this lesson, you will learn about mechanical dissipation, its origin and implications

- **Quantifying mechanical dissipation and its effects**
- **Contributions to mechanical dissipation from**
  - **surrounding medium**
  - **acoustic radiation to the substrate**
  - **loss in the resonator material**
- **Mitigation strategies**

Welcome to this lecture on mechanical dissipation. I'm Albert Schliesser. I'm a professor at the Niels Bohr Institute of Copenhagen University. In this lecture, you will learn about mechanical dissipation, its origin and its implications. We will start with quantifying mechanical dissipation and its effects. Then we will discuss the different contributions to mechanical dissipation from, in particular, the surrounding medium arising from acoustic radiation to the substrate and because of the loss in the resonator material itself. For each of these contributions, we will also discuss mitigation strategies.

Notes

Summary

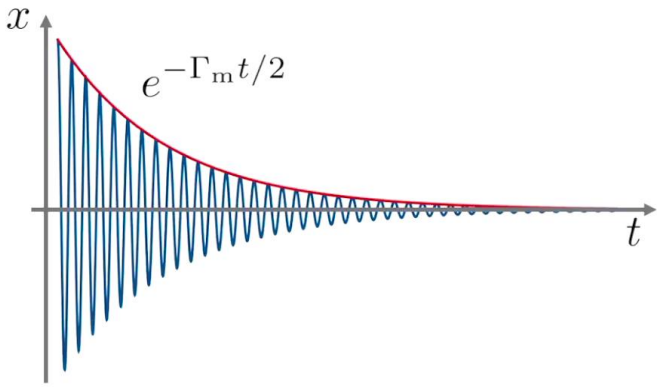
0m 00s

MECHANICAL DISSIPATION

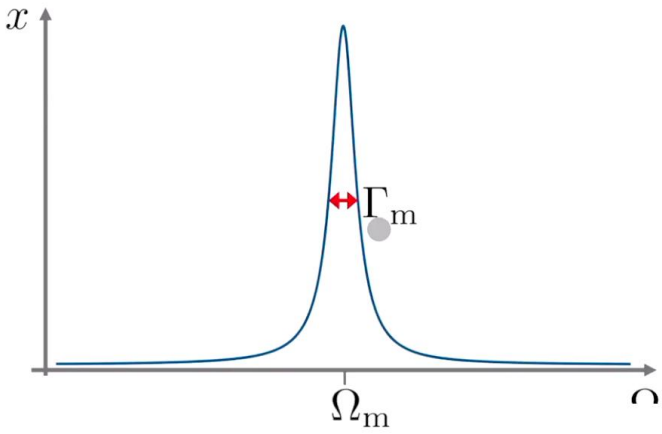
Mechanical motion as a damped driven harmonic oscillator:

$$m\left[\ddot{x}(t)+\Gamma_{\mathrm{m}}\dot{x}(t)+\Omega_{\mathrm{m}}^{2}x(t)\right]=F(t)$$

Free decay:



Response to an external force:



All right. So if we think of mechanical motion as a damped driven harmonic oscillator, it is this equation of motion we will be using. 'x' is the coordinate of the mechanical excitation and we have here this damping term which is basically a friction force so it corresponds to a force proportional to the velocity of the mechanical object. This leads, for example, to a free decay. So if we have a zero force, but an initial large amplitude, we see that the mechanical amplitude will be decaying following an envelope given by this expression here so this is an exponential decay and the amplitude decays with this rate gamma 'm' over two whereas the energy stored in the mechanical system would decay with an exponential rate of gamma 'm'. If instead we look in the frequency domain and we now sweep a sinusoidal force here with different frequencies, we would get this Lorentzian response that we have seen already many times and the mechanical dissipation shows up here as the linewidth gamma 'm'.

Notes

Summary

0m 51s

MECHANICAL DISSIPATION AND ITS EFFECTS

Dissipation rate, linewidth, inverse ringdown time: Γ_{m}

Thermal (Langevin) force noise: $S_{FF} = 4m\Gamma_{\mathrm{m}}k_BT$

Thermal decoherence rate: $\gamma \approx \frac{k_{\mathrm{B}}T}{\hbar\Omega_{\mathrm{m}}}\Gamma_{\mathrm{m}}$

Speaking more physically, a mechanical dissipation has many important effects as we just discussed. It leads to a ringdown of the mechanical amplitude or a linewidth in the response. It also leads to a force noise, the so-called Langevin force noise, the equivalent of electronic Johnson noise but here in the mechanical domain and this force noise is proportional to the dissipation rate gamma 'm' directly. It's also proportional to the temperature and this force noise plays an important role for example, for the capability of using mechanical devices as sensors for small forces or for example, also acceleration. On the other hand, if you want to do quantum experiments, the quantum state that you have prepared the mechanics in will decohere that means it loses its quantum features and that also happens at a rate that is proportional to the mechanical dissipation rate and again the temperature. So for many applications basically all conceivable applications, the dissipation rate here should be as low as possible.

Notes

Summary

2m 21s

MECHANICAL DISSIPATION AND ITS EFFECTS

Dissipation rate, linewidth, inverse ringdown time: $\Gamma_\mathrm{m} = \Omega_\mathrm{m}/Q$

Thermal (Langevin) force noise: $S_{FF} = 4m\Gamma_\mathrm{m}k_BT = 4m\dfrac{\Omega_\mathrm{m}}{Q}k_BT$

Thermal decoherence rate: $\gamma \approx \dfrac{k_\mathrm{B}T}{\hbar\Omega_\mathrm{m}}\Gamma_\mathrm{m} = \dfrac{k_\mathrm{B}T}{\hbar Q}$

with quality factor $Q = \dfrac{\Omega_\mathrm{m}}{\Gamma_\mathrm{m}} = \dfrac{2\pi W_\mathrm{stored}}{\Delta W_\mathrm{diss}}$

That is also why we refer to the ratio of the mechanical frequency and the mechanical dissipation rate as the quality factor. So the higher the quality factor the better. So if you look at this equation here this means the quality factor is really just the number of oscillations that we can undergo before the mechanical energy has decayed to basically one over 'E' of its starting value. The quality factor can alternatively be expressed as the ratio of the energy stored in the system and the energy dissipated in one oscillation cycle. And we can now use this 'Q' factor which is often actually used to quantify mechanical dissipation to re-express all these different equations here and again we find that the high 'Q' factor is really the thing that we want here. Interestingly, for the thermal decoherence rate the mechanical frequency actually drops out and we have a decoherence rate that is only proportional to 'T' over 'Q'.

Notes

Summary

3m 46s

CONTRIBUTIONS TO DISSIPATION

Dissipation can be caused by

- **the surrounding medium**
- **radiation of acoustic energy into the substrate**
- **intrinsic loss in the resonator material**
- **other effects**

$$\frac{1}{Q} = \sum_i \frac{1}{Q_i} = \frac{1}{Q_{\text{medium}}} + \frac{1}{Q_{\text{radiation}}} + \frac{1}{Q_{\text{intrinsic}}} + \frac{1}{Q_{\text{other}}}$$

Schmid, Villanueva, Roukes, *Fundamentals of Nanomechanical Resonators*, Springer (2016)

Air pressure [Pa]

But now what are the contributions to dissipation? There are really many and I have grouped them here into three main categories. I can have dissipation caused by the surrounding medium that could be liquid or in the case of optomechanics, it will typically be a very dilute gas. It could be radiation of acoustic energy into the substrate that holds the mechanical resonator. It could be intrinsic loss in the resonator material. This is something that is usually very difficult to avoid and there could be some other effects. And the final 'Q' factor that we're going to obtain is just going to be the reciprocal sum of all the 'Q' factors associated with these different effects.

Notes

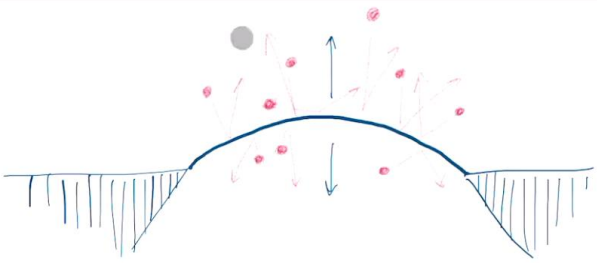
Summary

5m 11s

GAS DAMPING

Friction in surrounding gas

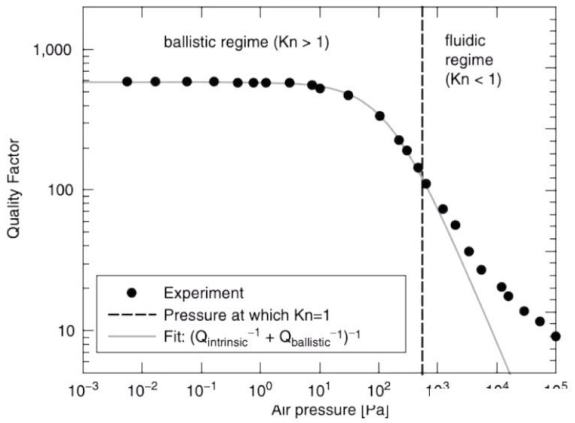
$$Kn = \frac{\text{gas mean free path}}{\text{resonator length scale}}$$



A) Fluidic/viscous regime $Kn \ll 1$

B) Ballistic/molecular regime $Kn \gg 1$

$$Q_{\text{gas}} = \frac{\rho h \Omega_{\text{m}}}{4} \sqrt{\frac{\pi}{2}} \sqrt{\frac{R_{\text{gas}} T}{M}} \frac{1}{p}$$



Mitigation measures:

- **Low-pressure operation**

Schmid, Villanueva, Roukes, *Fundamentals of Nanomechanical Resonators*, Springer (2016)

Now let us start with the surrounding medium and we will focus here on gas damping. And here too we have to consider two different regimes that are distinguished by the so-called Knudsen number which is the ratio between the mean free path of the gas particles and the typical length scale of the resonator. If this number is much smaller than one, we are in the so-called fluidic or viscous regime where we have to treat the gas as a viscous medium that exerts a drag on the moving mechanical object. Much more commonly encountered in optomechanics is the so-called ballistic or molecular regime with a Knudsen number much larger than one where we have a situation as is illustrated here. So if we think of our mechanical resonator to be a membrane as is shown here, which vibrates up and down just like a drum head. It is attached to a substrate here and, therefore, it can vibrate up and down like that. It's surrounded by these red gas molecules which just bounce off this membrane and in doing so they actually transfer some of their momentum and that leads to a damping of the mechanical oscillation.

Notes

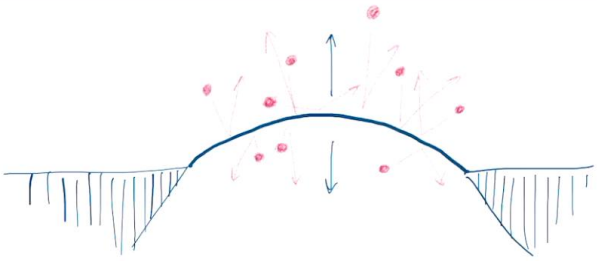
Summary

6m 08s

GAS DAMPING

Friction in surrounding gas

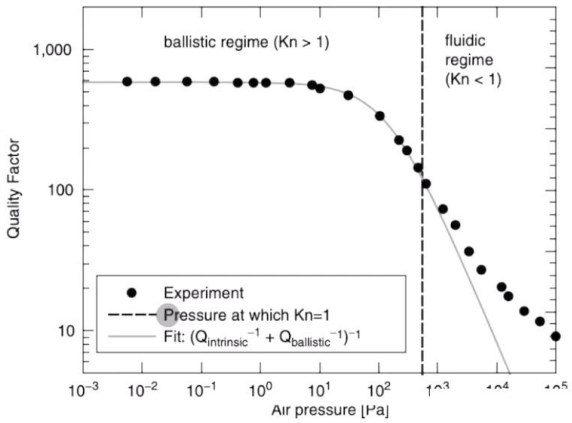
$$Kn = \frac{\text{gas mean free path}}{\text{resonator length scale}}$$



A) Fluidic/viscous regime $Kn \ll 1$

B) Ballistic/molecular regime $Kn \gg 1$

$$Q_{\text{gas}} = \frac{\rho h \Omega_{\text{m}}}{4} \sqrt{\frac{\pi}{2}} \sqrt{\frac{R_{\text{gas}} T}{M}} \frac{1}{p}$$



Mitigation measures:

- **Low-pressure operation**

Schmid, Villanueva, Roukes, *Fundamentals of Nanomechanical Resonators*, Springer (2016)

And this damping is proportional again to the square root of temperature and the mass of the molecules as well as the gas constant and importantly, it is inversely proportional to the pressure of this gas. So therefore, the way to go to mitigate this kind of damping is to operate the mechanical system at a very low environmental pressure so we will typically go to a high vacuum or even ultra-high vacuum to perform these experiments. Here you see some data. Here in the fluidic regime, you have a different pressure dependence but then in the ballistic regime, you really have a one over 'p' pressure dependence of the quality factor and eventually, you see a saturation here because of some other intrinsic quality factor limitation that has actually nothing to do with the gas. So that was for the medium.

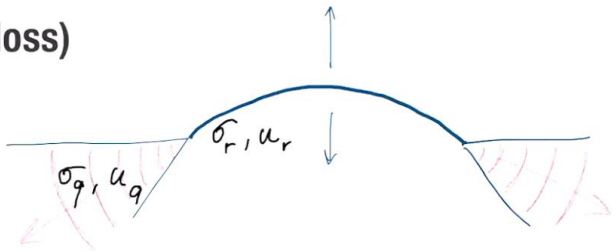
Notes

Summary

7m 40s

RADIATION LOSS

Radiation loss
(a.k.a. anchor, clamping or phonon tunneling loss)



Loss of acoustic energy into resonator substrate

Loss is determined by spectral and spatial mode overlap

$$\frac{1}{Q_{\text{radiation}}} = \frac{\pi}{2\rho_s \rho_r \Omega_m^3} \int_q \left| \int_S (\sigma_q \cdot u_r - \sigma_r \cdot u_q) \cdot d\hat{n} \right|^2 \cdot \delta\left(\Omega_m - \Omega(q)\right) dq$$

Wilson-Rae, Physical Review B **77**, 245418 (2008)

Now let's look into the damping into the substrate which I have labeled here as radiation loss but actually it comes with many names. It is also sometimes referred to as anchor loss, clamping loss or phonon tunneling loss but the basic idea is really very much the same. So if we go back to our vibrating membrane here then the fact that this is suspended here from this substrate, of course, allows the possibility that some acoustic energy is coupled into the substrate and then radiates away and never comes back. And to a good approximation, the loss that ensues from this mechanism is determined by a spectral and spatial overlap of the modes that live in our resonator and the modes that live in the substrate. These modes are characterized by some spatial distributions of displacement 'u' and stress sigma. In the substrate there are actually many modes which are enumerated here with the index 'q' whereas we have in only one resonator mode in this consideration here labeled with the subscript 'r'. And what we then get for this radiation 'Q' is that we have to evaluate these overlap integrals over some boundary surface here between the resonator and the substrate, overlap integrals between the stress in the substrate mode and the displacement in the resonator mode and vice versa, over the interface's surface.

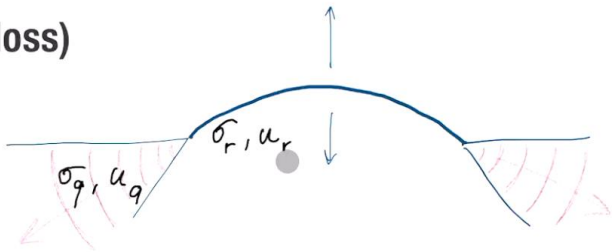
Notes

Summary

8m 48s

RADIATION LOSS

Radiation loss
(a.k.a. anchor, clamping or phonon tunneling loss)



Loss of acoustic energy into resonator substrate

Loss is determined by spectral and spatial mode overlap

$$\frac{1}{Q_{\text{radiation}}} = \frac{\pi}{2\rho_{\text{s}}\rho_{\text{r}}\Omega_{\text{m}}^3}\int_q \left|\int_S (\sigma_q \cdot u_{\text{r}} - \sigma_{\text{r}} \cdot u_q)\cdot d\hat{n}\right|^2 \cdot \delta\left(\Omega_{\text{m}} - \Omega(q)\right) dq$$

Wilson-Rae, Physical Review B **77**, 245418 (2008)

So this is the spatial overlap. We also need to have a spectral overlap which is basically given by this Dirac delta function here, that is the modes that matter, the substrate modes that matter are those whose frequency coincides with the resonance frequency of our resonator mode here.

Notes

Summary

10m 46s

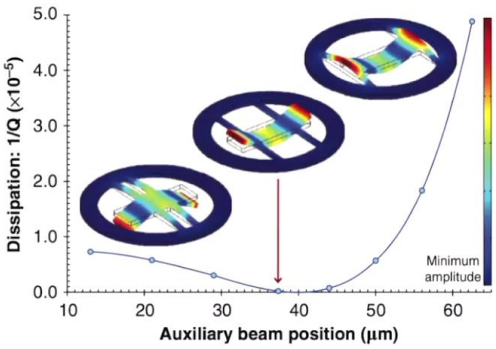
RADIATION LOSS

Clamping loss (a.k.a. radiation loss, phonon tunneling loss)

Loss is determined by spectral and spatial mode overlap.

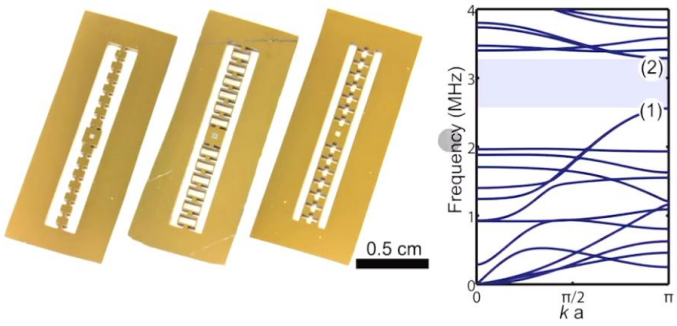
Mitigation measures:

Engineering geometry



Cole et al., Nature Comms. **2**, 231 (201)

Engineering substrate mode spectrum



Tsaturyan et al., Optics Express **6**, 6810 (2013)

And this basically directly gives us levers with which we can reduce the radiation loss. One is engineering the geometry in such a way that the spatial mode overlap becomes small. So here you see an example of where this is done. So the resonator mode here is the so-called free-free mode which is basically a bending of this little beam here and you see that if this resonator mode, if this resonator is supported with these small auxiliary beams at the positions where its displacement out of plane is zero, one gets the lowest dissipation whereas if it is supported where its displacement is large, one gets a larger dissipation simply because this allows the out coupling of acoustic energy through these beams, through these small beams into the substrate here. And another approach is to instead engineer the spectral overlap to be small and that can be done in the following way. So what you see here is a periodic structure which tailors the phononic density of states as shown here. So what you can actually do in such a periodic structure, you can open a band gap in which there are no phonon modes in the substrate here.

Notes

Summary

11m 12s

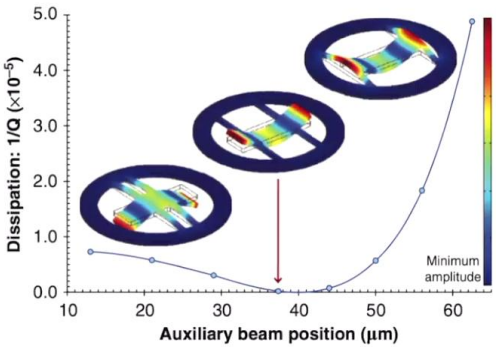
RADIATION LOSS

Clamping loss (a.k.a. radiation loss, phonon tunneling loss)

Loss is determined by spectral and spatial mode overlap.

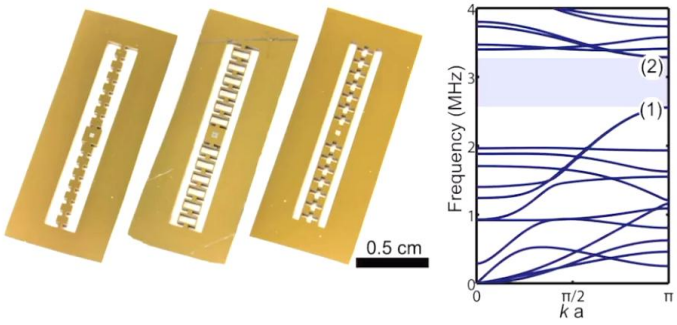
Mitigation measures:

Engineering geometry



Cole et al., Nature Comms. **2**, 231 (201)

Engineering substrate mode spectrum



Tsaturyan et al., Optics Express **6**, 6810 (2013)

That means if I have a resonator mode, in this case in this central small square here we have again such a membrane and this resonator frequency lies in this band gap, there's no possibility that this resonator radiates its energy out into the substrate rather it remains confined to the center here and therefore, the dissipation is small. Of course, the maybe most extreme version of this approach here is to entirely do a way with a connection to the substrate and levitate the mechanical system in an electromagnetic trap, for example, an optical tweezer.

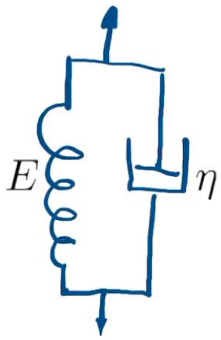
Notes

Summary

12m 53s

INTRINSIC LOSS

Linear visco-elastic materials: $\sigma(t) = E\varepsilon(t) + \eta\dot{\varepsilon}(t)$



Stress and strain oscillate out of phase:

$$\varepsilon = \varepsilon_0 \sin(\Omega t)$$

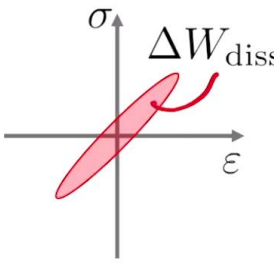
$$\sigma = \sigma_0 \sin(\Omega t + \delta)$$

Resulting friction loss:

$$\Delta W_{\text{diss}} = \oint \sigma d\varepsilon = \int_0^{2\pi/\Omega_{\text{m}}} \sigma \frac{d\varepsilon}{dt} dt = \pi \sigma_0 \varepsilon_0 \sin\delta$$

$$W = \frac{1}{2}\sigma_0 \varepsilon_0 \cos\delta$$

$$Q = \frac{2\pi \cdot W}{\Delta W_{\text{diss}}} = \frac{1}{\tan\delta} = \frac{E'}{E''} = \frac{E}{\eta\Omega}$$



Schmid, Villanueva, Roukes, *Fundamentals of Nanomechanical Resonators*, Springer (2016)

Now finally, if you have suppressed both the dissipation into the surrounding medium and to a substrate, the resonator itself will also dissipate and that is because most materials that we're actually working with have to be described as linear viscoelastic materials, meaning that the stress-strain relation isn't just this simple Hooke's law here as given by this first term but we also have a stress that is proportional to the time derivative of the strain which is equivalent to a friction force basically a force proportional to the velocity. This is often illustrated with diagrams like that where you have the springs and these kind of dashed parts which basically represent the response of the elastic kind and the viscous kind here with these two elements. Now an immediate consequence of this relation here is that stress and strain will not oscillate in phase anymore. Indeed if we say let the strain oscillate here sinusoidally, I will get a small phase shift with which the stress is oscillating assuming that, of course, the second term here is small which is typically the regime in which we're working. In this case, we can actually calculate the quality factor using this expression of the ratio of the stored energy and the dissipated energy.

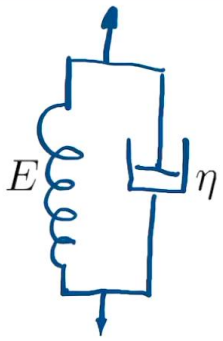
Notes

Summary

13m 43s

INTRINSIC LOSS

Linear visco-elastic materials: $\sigma(t) = E\varepsilon(t) + \eta\dot{\varepsilon}(t)$



Stress and strain oscillate out of phase:

$$\varepsilon = \varepsilon_0 \sin(\Omega t)$$

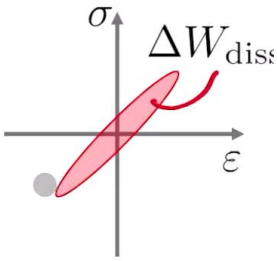
$$\sigma = \sigma_0 \sin(\Omega t + \delta)$$

Resulting friction loss:

$$\Delta W_{\text{diss}} = \oint \sigma d\varepsilon = \int_0^{2\pi/\Omega_{\text{m}}} \sigma \frac{d\varepsilon}{dt} dt = \pi \sigma_0 \varepsilon_0 \sin\delta$$

$$W = \frac{1}{2}\sigma_0 \varepsilon_0 \cos\delta$$

$$Q = \frac{2\pi \cdot W}{\Delta W_{\text{diss}}} = \frac{1}{\tan\delta} = \frac{E'}{E''} = \frac{E}{\eta\Omega}$$



Schmid, Villanueva, Roukes, Fundamentals of Nanomechanical Resonators, Springer (2016)

Indeed we get the dissipated energy by integrating over one oscillation cycle the product of stress and strain like that. And if we carry out this integral, we find that it's proportional to the sign of this small dephasing delta. We can do a similar analysis for this stored energy. We find it is proportional to the cosine of this multiphasing delta. Therefore, the quantity factor is given by one over the tangent of delta and that is why delta is also often called the loss angle. We can furthermore relate this actually to these parameters up here or the real 'E' prime and imaginary 'E' prime-prime part of the of the dynamic modulus of the medium. So here's just an illustration of what this dissipated energy corresponds to. Again if we go through an oscillation cycle, sigma and epsilon aren't precisely in phase and therefore, we have an area here, an enclosed area here that corresponds to the dissipated energy.

Notes

Summary

15m 34s

THERMOELASTIC DAMPING

Loss angle can be frequency dependent

In thermoelastic damping, deformation-induced heating equilibrates via heat diffusion

$$\frac{1}{Q_{\mathrm{te}}} = \Delta_{\mathrm{te}} \frac{\Omega_{\mathrm{m}} \tau_{\mathrm{te}}}{1 + (\Omega_{\mathrm{m}} \tau_{\mathrm{te}})^2}$$

Mitigation measures:

- **Engineering geometry and material**
- **Reducing temperature**

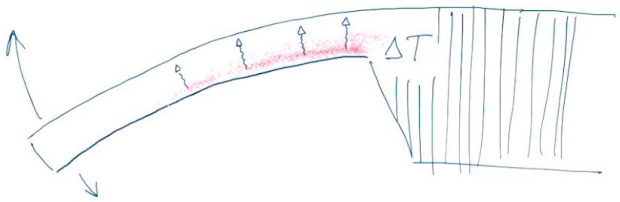
Zener model

Relaxation strength

$$\Delta_{\mathrm{te}} = \frac{E\alpha^2 T}{\rho c_p}$$

Relaxation time

$$\tau_{\mathrm{te}} = \frac{h^2}{\pi^2} \frac{\rho c_p}{\kappa}$$



Now the loss angle can be frequency dependent itself and an important example for micromechanical systems is thermoelastic damping where this is happening and the frequency dependence here arises because there is a characteristic time scale and this characteristic time scale is that of a heat diffusion through the sample because what's happening here is that the deformation, for example of a bending cantilever, causes local heating. It causes heating basically where the material gets compressed and a slight cooling where the material is dilated. This is due to the fact that we have this thermal expansion coefficient here and this temperature gradient is then compensated by heat diffusion and we have a characteristic time scale which is this relaxation time here at which this temperature gradient is actually equilibrated by heat diffusion. So you see here what plays a role is the thickness 'h' of this cantilever and basically the diffusion constant for heat over here. And in this case, we actually get this strongest reduction of the quality factor if the mechanical oscillation frequency just matches exactly this time scale at which the heat diffusion equilibrates this temperature difference.

Notes

Summary

17m 01s

THERMOELASTIC DAMPING

Loss angle can be frequency dependent

In thermoelastic damping, deformation-induced heating equilibrates via heat diffusion

$$\frac{1}{Q_{\mathrm{te}}} = \Delta_{\mathrm{te}} \frac{\Omega_{\mathrm{m}} \tau_{\mathrm{te}}}{1 + (\Omega_{\mathrm{m}} \tau_{\mathrm{te}})^2}$$

Mitigation measures:

- **Engineering geometry and material**
- **Reducing temperature**

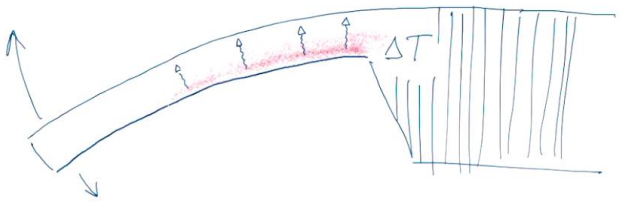
Zener model

Relaxation strength

$$\Delta_{\mathrm{te}} = \frac{E\alpha^2 T}{\rho c_p}$$

Relaxation time

$$\tau_{\mathrm{te}} = \frac{h^2}{\pi^2} \frac{\rho c_p}{\kappa}$$



So this is an example for a rather generic effect namely, a relaxation effect which is actually covered by the so-called Zener model and leads to a quality factor of this kind where we have a relaxation strength delta here and then a characteristic time scale tau at which this relaxation is happening. For thermoelastic damping, the most obvious ways to mitigate it is to engineer the geometry and the material, in particular, very thin cantilevers for example, will have low thermoelastic damping and of course, one can try to reduce for example, this thermal expansion coefficient by using the proper materials or go to low temperatures where this effect becomes small. However, at room temperature and for typical micrometer sized mechanical devices, for example in silicon, thermoelastic damping can be a limiting factor.

Notes

Summary

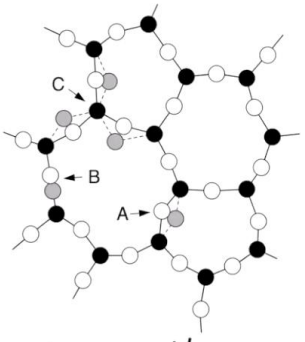
19m 03s

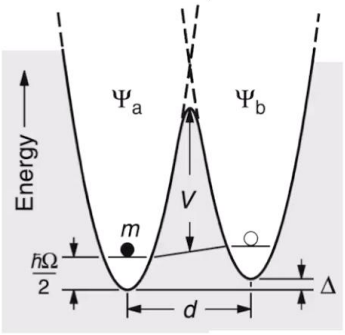
TWO-LEVEL SYSTEMS (TLS)

Microscopic defects can assume different configurations modelled by asymmetric double-well potential

With potentially broad distribution $P(V, \Delta)$ of energy parameters

Oscillating strain fields (phonons) couple to TLS





nss, Hunklinger, *Low-Temperature Physics*, Springer (2005)

Now eventually, we have in the material microscopic defects that can assume different configurations. This can be, you know, crystal defects in a crystalline material grain boundaries or if you have, for example, amorphous materials then you have, of course, a slightly irregular arrangement here of atoms and these atoms can actually then assume different equilibrium positions. And this is modeled by an asymmetric double-well potential so again, say this atom here can be in two different positions, each of these positions corresponds to one of these minima here in this double-well potential. They are separated by a potential barrier of height 'V' and they have a slight energy difference of about delta. Now of course, if in particular, these are defects say, in an amorphous material, these defects are not necessarily all the same but we will have to model them with a broad distribution in these energy parameters 'V' and delta. And the thing is now that these two-level systems which can also lead to dielectric losses also coupled to strain fields so they're coupled to basically the phonon modes that we are interested in.

Notes

Summary

20m 16s

TWO-LEVEL SYSTEMS (TLS)

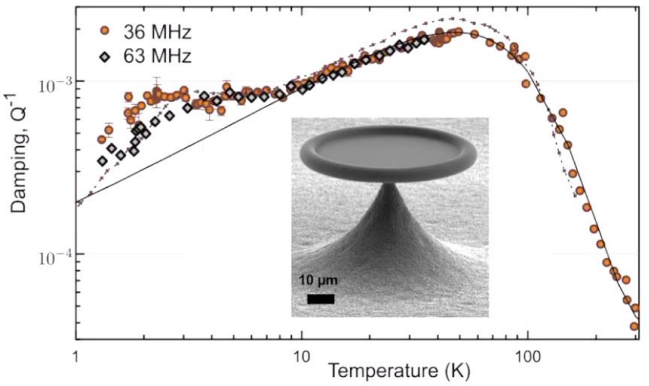
Oscillating strain fields (phonons) couple to TLS

Leading to mechanical dissipation through

- **Thermally activated relaxation**
- **Tunneling relaxation**
- **Direct phonon absorption**

All contributing to E''_{TLS}

with strong temperature dependence!



Arcizet et al., Physical Review A **80**, 021803 (2009)

nss, Hunklinger, *Low-Temperature Physics*, Springer (2005)

And in this way they can lead to mechanical dissipation and there are various different regimes. We can have relaxation mechanisms where we can actually use again a Zener model but now we have to take into account that we have a broad distribution of these energy parameters and their relaxation can be thermally activated so we would have a Arrhenius kind of law. We could take many phonons from the environment and jump from one state to the other at sufficiently low temperatures which is typically on the order of a few kelvin or so. There can be a transition where we only have tunneling relaxation so the two-level systems can still switch between the two states through the mechanism of tunneling and then at very low temperatures, we don't have a relaxation effect anymore but rather these two-level systems can directly absorb phonons. For the latter effect to happen here, we really need to be at temperatures very low compared even to the energy of a single phonon which is essentially because in order for this direct phonon absorption to happen, we need to polarize these two-level systems meaning we need to have a higher probability for the two-level system to be in its lower energy state as compared to its higher energy states.

Notes

Summary

22m 01s

TWO-LEVEL SYSTEMS (TLS)

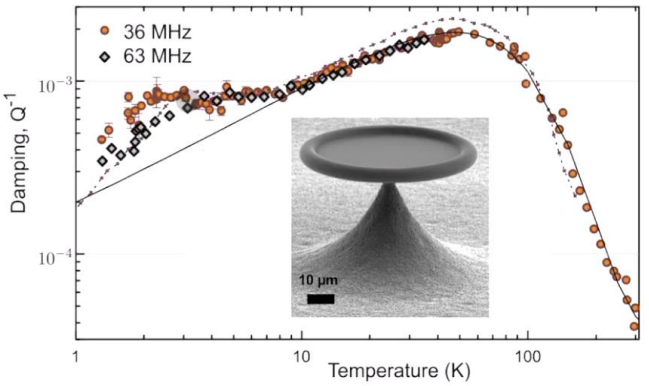
Oscillating strain fields (phonons) couple to TLS

Leading to mechanical dissipation through

- **Thermally activated relaxation**
- **Tunneling relaxation**
- **Direct phonon absorption**

All contributing to E''_{TLS}

with strong temperature dependence!



Arcizet et al., Physical Review A **80**, 021803 (2009)

nss, Hunklinger, *Low-Temperature Physics*, Springer (2005)

So here's an example of the dissipation caused by two-level systems. On one of these silica resonators here, we see a really pronounced temperature dependence and at these higher temperatures here, the dissipation is actually dominated by thermally activated relaxation whereas this plateau and then the roll-off here at low temperature is actually caused by tunneling relaxation. The direct phonon absorption cannot be seen in this example.

Notes

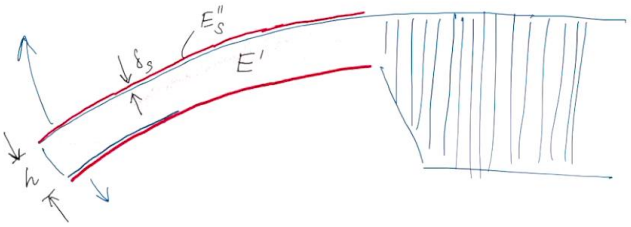
Summary

23m 58s

TWO-LEVEL SYSTEMS (TLS)

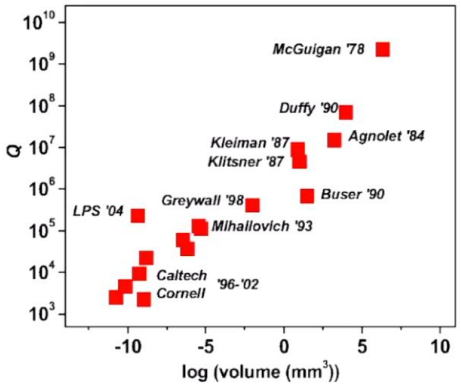
Lossy materials
(e.g. containing high density of TLS)
are often in a thin surface layer

$$Q_{\text{surface}} = \frac{h}{6\delta_S}\frac{E'}{E''_S}$$



Mitigation measures:

- **Surface treatment (for surface loss)**
- **Reducing temperature**
- **Dissipation dilution**



Ekinci, Roukes, Rev. Sci. Inst. **76**, 061101 (2005)

It should be noted for two-level systems that the lossy materials that contain a high density of two-level systems is very frequently in a thin surface layer. So we may have a certain kind of two-level systems with a low density in the bulk of the resonator but the loss is actually dominated by a thin surface layers, a layer which has a much higher imaginary part here of the dynamic modulus and then the 'Q' that we get depends also on the thickness of this layer as compared to the thickness of the entire device. And a hint that in many systems there is really the surface that plays the dominant role comes, for example, from this overview here of the logarithmic volume versus the 'Q' factor which shows a scaling that is proportional to the surface-to-volume ratio and therefore, indicates that if you have nanoscale systems with a lot of surface then you will typically end up with relatively low quality factors whereas for macroscopic systems, this is a piece of silicon of several kilograms, you can have high quality factors on the order of ten to the nine. So for surface losses, of course, what you can do is devise different methods for surface treatment such as etching or annealing.

Notes

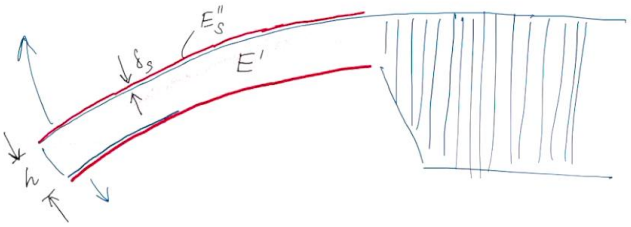
Summary

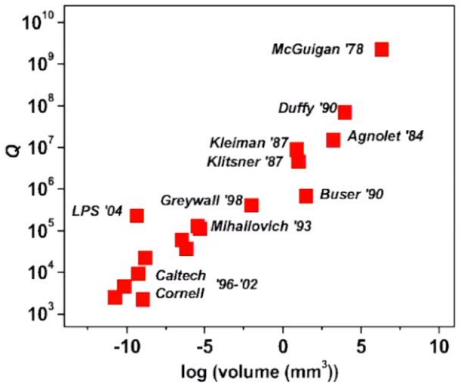
24m 32s

TWO-LEVEL SYSTEMS (TLS)

Lossy materials
(e.g. containing high density of TLS)
are often in a thin surface layer

$$Q_{\text{surface}} = \frac{h}{6\delta_S}\frac{E'}{E''_S}$$





Ekinci, Roukes, Rev. Sci. Inst. **76**, 061101 (2005)

Mitigation measures:

- **Surface treatment (for surface loss)**
- **Reducing temperature**
- **Dissipation dilution**

Of course, one can always reduce the temperature as we have seen for two-level systems, this tends to reduce the damping and then there's a last way out which is known as dissipation dilution, which I would like to briefly explain here in the last couple of slides.

Notes

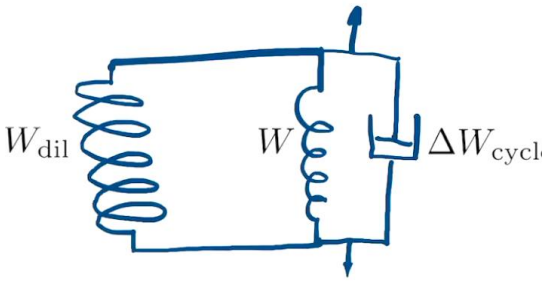
Summary

26m 21s

DISSIPATION DILUTION

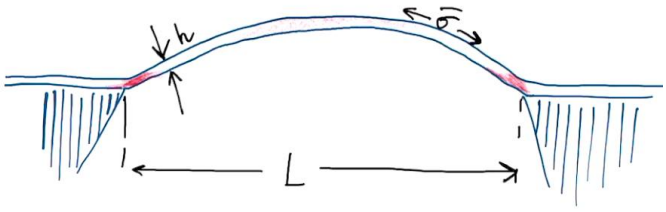
An additional lossless potential dilutes dissipation

$$Q = 2\pi \frac{W_{\mathrm{dil}} + W}{\Delta W_{\mathrm{diss}}}$$



Can be realized in stressed string and membrane resonators, where thanks to a geometric nonlinearity

$$Q = 2\pi \frac{W_{\mathrm{tension}}(\bar{\sigma}) + W_{\mathrm{bending}}}{\Delta W_{\mathrm{bending}}}$$



So the idea of dissipation dilution is to introduce in addition to the potential that we have discussed so far, another lossless mechanical potential which stores energy and thereby, dilutes the dissipation that we invariably have. This is then referred to as a dissipation dilution. One example where this can be realized are stressed string and membrane resonators which look again as we have discussed previously like this. We have a substrate here which is hatched like that and then we have this membrane that can oscillate out of plane and if this device is under high tensile stress then actually I can store a lot of energy in the fact that I have to elongate this membrane here if I want to get this kind of displacement and I have to elongate it against the high in-plane stress. So this will cost and therefore, store a lot of energy. However, due to a geometric nonlinearity, the loss will only be caused to low order in the displacement will only be caused by the bending of the material and the bending will happen typically here at the clamping points and of course, also here we're just bending the entire structure.

Notes

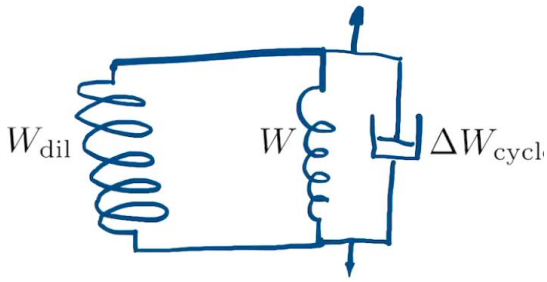
Summary

26m 40s

DISSIPATION DILUTION

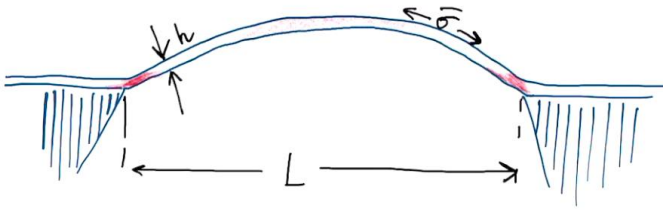
An additional lossless potential dilutes dissipation

$$Q = 2\pi \frac{W_{\text{dil}} + W}{\Delta W_{\text{diss}}}$$



Can be realized in stressed string and membrane resonators, where thanks to a geometric nonlinearity

$$Q = 2\pi \frac{W_{\text{tension}}(\bar{\sigma}) + W_{\text{bending}}}{\Delta W_{\text{bending}}}$$



But now the important thing is here that the quantity factor now is no more given only by material parameters rather since the dominating stored energy is this first term here, we have the quality factor as a ratio of the energy stored in tension and the energy dissipated through bending. So what I can do is I can basically engineer the geometry so that it optimizes this ratio.

Notes

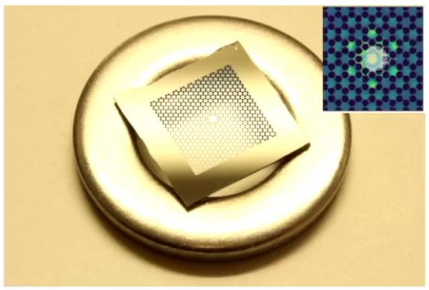
Summary

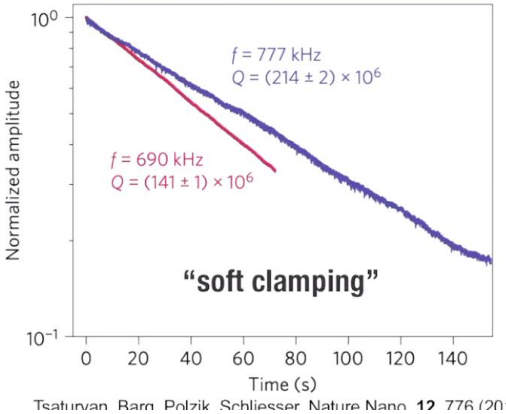
28m 21s

DISSIPATION DILUTION

In stressed string and membrane resonators

$$\frac{1}{Q} = f(\lambda) \cdot \frac{E''}{E'} \quad \textbf{with} \quad \lambda = \frac{h}{L}\sqrt{\frac{E}{12\bar{\sigma}}}$$





Tsaturyan, Barg, Polzik, Schliesser, Nature Nano. **12**, 776 (2017)

Conducive to dissipation dilution:

- **High aspect ratio**
- **High tensile stress**
- **Mode shapes which minimize bending**

So this means that in such a geometry in stressed string and membrane resonators, the inverse quality factor then is actually a product of the what is sometimes referred to intrinsic quality factor so the ratio of the imaginary and real part of the dynamic modulus times a prefactor which is given by geometry and stress and this is a function of the parameter lambda which is again here an aspect ratio and involves the pre-stress of the resonator. So we will get high dissipation dilution if we have a high aspect ratio so if we have a very thin resonator which is relatively large, if we have high tensile stress and if we have mode shapes which minimize the bending. And to give you an example here where this works particularly well in an approach that is called soft clamping. We can use a membrane that is some tens of nanometers thick but hundreds of micrometers wide making this aspect ratio here large. It is under a high tensile stress of about one gigapascal and we minimize the bending by embedding it here in a phononic crystal. So the resonator itself is this defect here as you see here in this measurement. The out-of-plane displacement is given by this bright shades of Grey so the displacement happens here on this island.

Notes

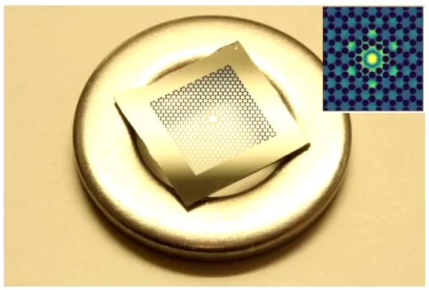
Summary

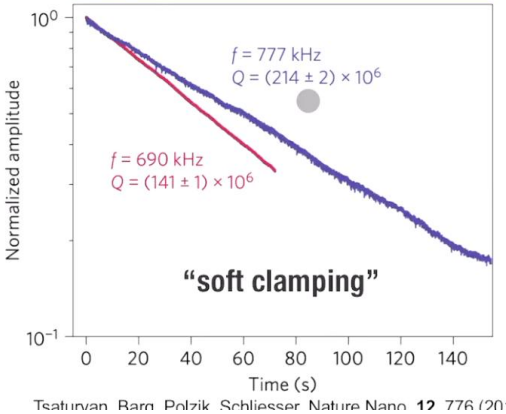
28m 59s

DISSIPATION DILUTION

In stressed string and membrane resonators

$$\frac{1}{Q} = f(\lambda) \cdot \frac{E''}{E'} \quad \textbf{with} \quad \lambda = \frac{h}{L}\sqrt{\frac{E}{12\bar{\sigma}}}$$





Tsaturyan, Barg, Polzik, Schliesser, Nature Nano. **12**, 776 (2017)

Conducive to dissipation dilution:

- **High aspect ratio**
- **High tensile stress**
- **Mode shapes which minimize bending**

The phononic crystal will, of course, suppress radiation loss but it will also avoid the strong bending at the resonator edge here at the resonator suspension and thereby, allow a very advantageous dilution factor 'f' of lambda here. And so in this way, we can actually add room temperature for around one megahertz resonators achieve quality factors far in excess of one hundred million.

Notes

Summary

30m 42s

SUMMARY

- **Many mechanisms contribute to mechanical damping, related to surrounding medium, coupling to the substrate, and the resonator itself**
- **Low dissipation / high Q factors are only achieved if all of them are mitigated**
- **Decisive influence by material, geometry and temperature**

Okay. So to summarize when it comes to mechanical dissipation we have to take into account that many mechanisms contribute. They are related to the surrounding medium, the coupling to the substrate and the resonator itself. If you want to have low dissipation or high 'Q' factors, the only way to get it is to mitigate all of them and it is not enough to control only one of them and the most decisive influence on the 'Q' factor that you will obtain is given by the resonator material, the geometry and also the temperature.

Notes

Summary

31m 21s