

OUTLINE

In this lesson, you will learn about Optomechanically Induced Transparency (OMIT), a phenomenon that allows to control optically the transmission of light through an optomechanical system.

- Reminder about atomic Electromagnetically Induced Transparency (EIT)
- Analogy with Optomechanically Induced Transparency
- Applications of Optomechanically Induced Transparency:
 - Optical switching
 - Slow light
 - Pulse storage

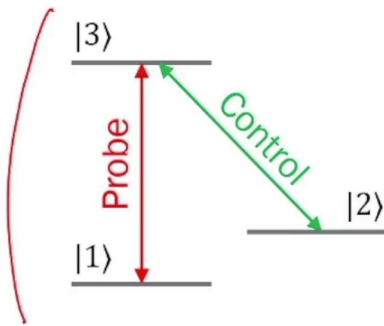
Welcome to this video on optomechanically induced transparency. My name is Samuel Deléglise from Laboratoire Kastler Brossel. So in this video, you will learn about a phenomenon that allows to control the transmission of a light beam through an optomechanical system via the presence or the absence of a second auxiliary light beam. So this phenomenon share strong analogy with a well-known effect in atomic physics, which is called Electromagnetically Induced Transparency or EIT and I will present both of these effects in order to highlight the analogies and the specificities of OMIT as compared with EIT. Finally, we'll present some possible applications of OMIT namely, the possibility to use a light beam to optically switch another light beam or to slow or even stop a pulse of light for instance, realize delays or buffers in optical transmission lines.

Notes

Summary

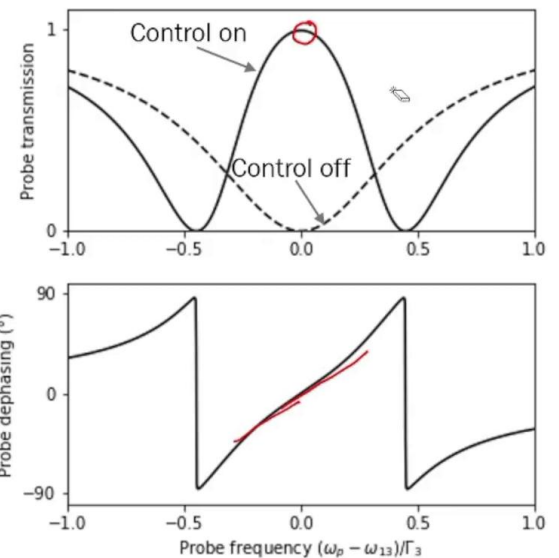


ELECTROMAGNETICALLY INDUCED TRANSPARENCY



Interference effect in a 3-level atom subjected to 2 laser beams:

- Possible excitation pathways interfere destructively
- Probe light is transmitted
- Transmission is accompanied by strong dispersion



Harris, Physics Today 50, 36-42 (1997)

Lukin, Imamoglu, Nature 413, 273-276 (2001)

Fleischhauer, Imamoglu, Marangos, RMP 77, 63

So EIT is an interference effect that occurs in a 3-level atomic systems illuminated by two laser beams. So the interference between the various excitation pathways gives rise to an anomalous transmission of the probe beam and this transparency window is accompanied by very strong dispersion that leads to a slow group velocity as we will see towards the end of this video. So let's try first to get an intuitive picture for the physics and the origin of EIT.

Notes

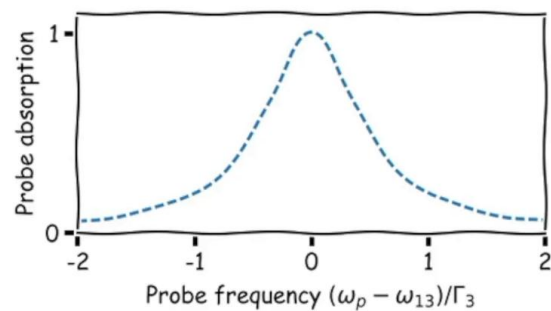
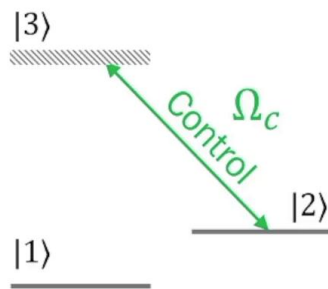
Summary



1m 10s

ELECTROMAGNETICALLY INDUCED TRANSPARENCY

A dense medium absorbs light resonant with an atomic transition...



... however, in a 3-level atom, a pump beam can modify the excitation spectrum (dressed-states).

So we first maybe need to explain why in the first place light gets normally absorbed in a dense atomic medium. So let's consider an ensemble of atoms and we denote by one, their electronic ground state and three, an electronic excited state and let's illuminate these atoms with a nearly resonant probe beam of frequency ω_p . Naturally, some of these atoms in this situation will be excited in the state three and this excited state has a finite lifetime due to spontaneous emission and let's call Γ_3 the rate at which these atoms relax towards the ground state with spontaneous emission. Because energy is lost into this in current spontaneous emission photons in the process, the probe beam gets absorbed and you can see here the typical shape of the absorption spectrum which is Lorentzian as a function of the probe frequency. So this is the basic reason why for instance, if you shoot a laser beam towards a brick wall, for instance, the laser beam doesn't go through. However, in the presence of a third level in the atomic system one can make the atoms transparent for the probe beam at resonance and the way to do that is to tune the control beam resonant with this two-three transition.

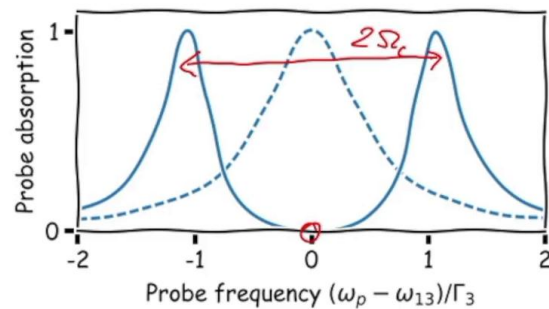
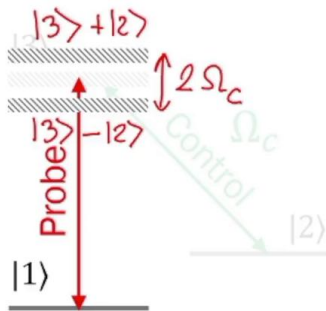
Notes

Summary



ELECTROMAGNETICALLY INDUCED TRANSPARENCY

A dense medium absorbs light resonant with an atomic transition...



... however, in a 3-level atom, a pump beam can modify the excitation spectrum (dressed-states).

If we treat now the control beam as a classical field, one can show that the bare atom plus classical field becomes an equivalent atom with the excited state being a split-level where here we have symmetric superposition of the level three plus two and here the anti-symmetric three minus two. So this effect is frequency domain counterpart of classical Rabi oscillation and the spacing between these levels here is given by the Rabi frequency two omega 'c'. Now, if we illuminate the system with the prob beam resonant with the one-three transition, we can see that there is no state in the excitation spectrum such that the probe beam cannot be absorbed at resonance. In fact, the absorption spectrum looks like this. We have two peaks separated by the Rabi frequency two omega 'C'. So in this so-called strong coupling regime where omega 'C' is much larger than the excited states decay rate, we see that EIT is a fairly straightforward consequence of the Rabi level splitting.

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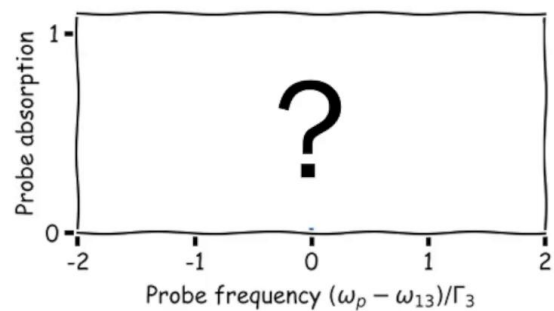
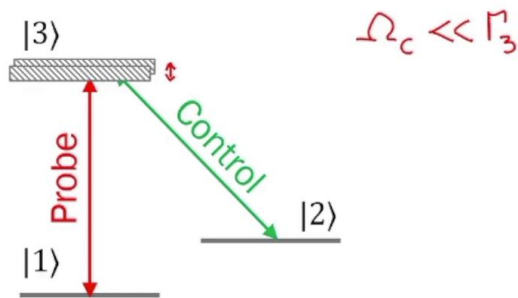
Summary



3m 27s

ELECTROMAGNETICALLY INDUCED TRANSPARENCY

A dense medium absorbs light resonant with an atomic transition...



... however, in a 3-level atom, a pump beam can modify the excitation spectrum (dressed-states).

However, things get more subtle when we consider the weak coupling regime Ω_c much smaller than Γ_3 . Because in this regime, the two excited states overlap due to the finite linewidth and there is not really any more gap in the excitation spectrum. So what do you think the absorption spectrum for the probe beam looks like in this scenario?

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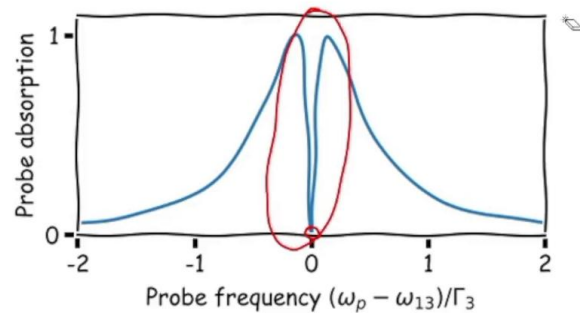
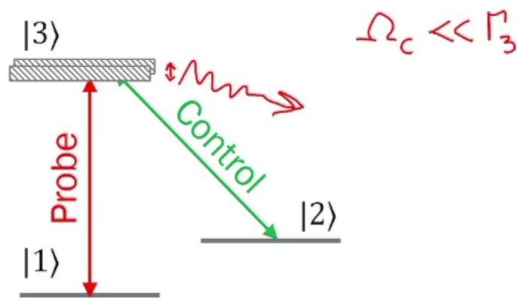
Summary



4m 56s

ELECTROMAGNETICALLY INDUCED TRANSPARENCY

A dense medium absorbs light resonant with an atomic transition...



... however, in a 3-level atom, a pump beam can modify the excitation spectrum (dressed-states).

I give you a few seconds to think about what the curve would look like. You can see here the typical absorption spectrum observed in this weak coupling regime. What we see is a very sharp deep here with, in particular, here the perfect transmission for the probe beam at resonance with the one-three transition. So to understand this effect, we have to realize that in this regime there is not really a way to tell by simply looking at the spontaneous emission photon from which of the excited state this photon was emitted. So we are here in a situation where two competing processes lead to the same final state and it is well-known that in such a situation we'll have interferences. So this deep in the absorption spectrum corresponds to destructive interference between the two excitation pathways. To get a clearer picture, we can actually write the Hamiltonian of the system in the presence of the two beam.

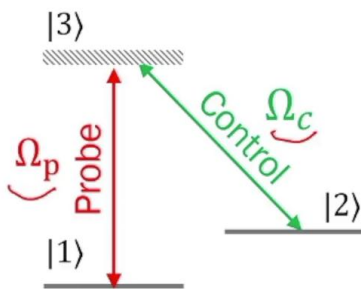
Notes

Summary



5m 26s

DARK STATE EXPLANATION OF EIT



Hypotheses:

- Probe and control fields are resonant
- Each of them drive (classical) Rabi oscillations on their respective transition

Hamiltonian (in the interaction picture):

$$\hat{H}/\hbar = \Omega_c |3\rangle\langle 2| + \Omega_p |3\rangle\langle 1| + h.c.$$

Atoms in the following state are never excited towards $|3\rangle$

$$|\Psi\rangle = \Omega_c |1\rangle - \Omega_p |2\rangle$$

$$\hat{H}|\Psi\rangle = (\Omega_c \Omega_p - \Omega_p \Omega_c) |\Psi\rangle = 0$$

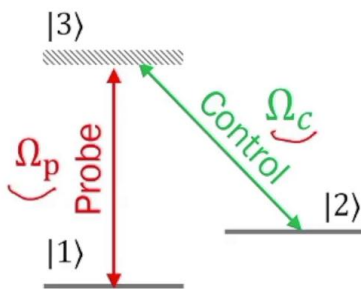
For this, we consider first of all that the probe beam and the control are resonant with their respective transition and we designate by Ω_p the Rabi frequency induced by the probe beam and Ω_c the Rabi frequency induced by the control field. The Hamiltonian is then quite simple. The control field couples the two-three transition and the probe field couple the one-three transition. This is a generalization of the Hamiltonian for classical Rabi oscillations in the case of a three-level atom. So now that we have written this Hamiltonian, we can see that there exists a particular combination of the ground state that is not coupled to the excited states. In other words, $\hat{H}|\Psi\rangle = 0$. So once again the fact that this state is not coupled to the excited state can be seen as a destructive interference between the amplitude of probability for this two excitation process. So we call such a state a dark state because if this atom is in this state, it will stay there forever and no spontaneous emission will occur. So we are in a situation very analogous to optical pumping.

Notes

Summary



DARK STATE EXPLANATION OF EIT



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Atoms in the following state are never excited towards $|3\rangle$

$$|\Psi\rangle = \Omega_c |1\rangle - \Omega_p |2\rangle \quad \hat{H}|\Psi\rangle = (\Omega_c \Omega_p - \Omega_p \Omega_c) |\Psi\rangle = 0$$

→ Very quickly, in the presence of the 2 laser fields, the atoms are *optically pumped* towards the dark state $|\Psi\rangle$.

Any other linear combination of the atom in the ground state will rapidly be excited to the upper state whereas if the atom is in the dark state, it will stay there forever. So consequently after only a few cycles of spontaneous emission, all the population will be trapped in this dark state and spontaneous emission will completely stop. And no spontaneous emission also means that the medium is entirely transparent for the probing. So this is as far as I want to go with the explanation of EIT and we are now ready to set the stage for optomechanically induced transparency.

Notes

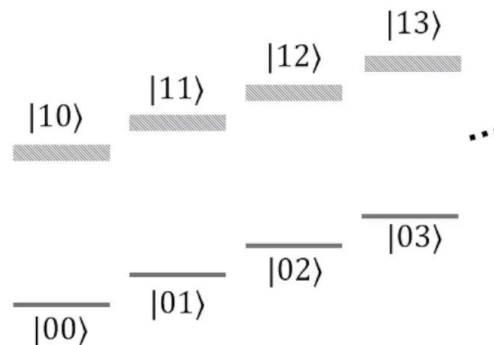
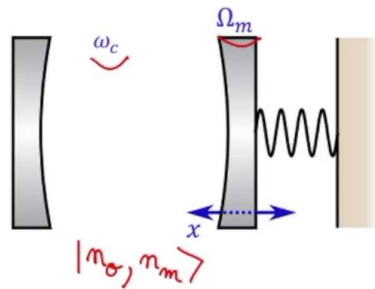
Summary



8m 19s

OPTOMECHANICALLY INDUCED TRANSPARENCY

A canonical optomechanical system driven by two laser fields...



Schliesser PhD thesis (2009)
Agarwal and Huang PRA (2010)

So it was realized approximately ten years ago that a situation similar to EIT could occur in an optomechanical system and maybe the best way to visualize this analogy is to take the canonical cavity optomechanical system and to draw its excitation spectrum. So we take a mechanical resonator of frequency ω_m and couple to a cavity a frequency ω_c . And we will index with two integer numbers the eigenstate. The first number is the number of photons in the optical cavity and the second one the number of phonons in the mechanical resonator. So rigorously, these states are the eigenstates of the uncoupled systems. However, because the vacuum optomechanical coupling rate is a very small number, we can in a very good approximation take these as the eigenstate of the coupled system. So if we now place this eigenstate on an energy diagram, we get the following. Because each time we add an optical photon, we increase the energy by $\hbar\omega_c$ and each time we add a phonon in the mechanical resonator, the energy increase by $\hbar\omega_m$.

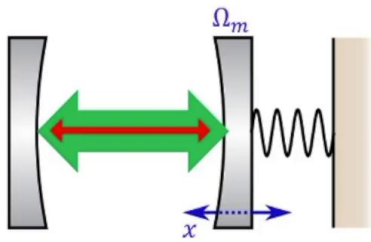
Notes

Summary



8m 59s

MECHANICAL DARK STATE ?

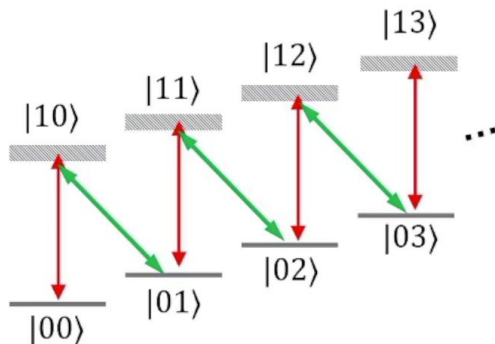


Hypotheses:

- Pump and probe fields on resonance with their transitions
- Resolved sideband regime $\kappa \ll \Omega_m$

Hamiltonian in the interaction picture:

$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + \sqrt{\kappa} \alpha_p \hat{a}^\dagger + h.c.$$



So now if we illuminate this system with a near resonant probe beam we'll excite the cavity in close analogy with the atomic K's and because of photon losses in this cavity, the probe beam will be absorbed and the maximum of absorption occurs when the probe beam is on resonance with the cavity mode. So this is this probe beam that we will try to transmit through the optomechanical system in the phenomenon of OMIT. So the last ingredient we need for this is an intense probe beam that we will tune on the lower optomechanical sideband so one mechanical resonance frequency below the cavity frequency and this probe beam will activate a beam splitter interaction where a photon can be swapped into a phonon so this corresponds to this diagonal transition in this diagram. And if we now look at this diagram, the resemblance with EIT is striking in particular. We will now see that there do exist as well a dark state that prevents cavity excitation. So to realize this we can write the Hamiltonian of the system and for this we make the following assumption.

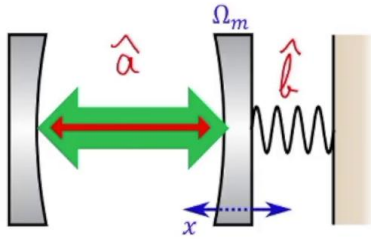
Notes

Summary



10m 33s

MECHANICAL DARK STATE ?



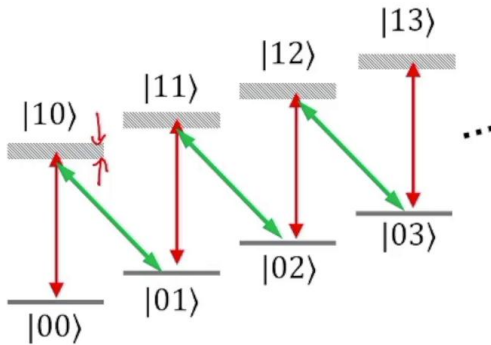
Hypotheses:

- Pump and probe fields on resonance with their transitions
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Hamiltonian in the interaction picture:

$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + \sqrt{\kappa} \alpha_p \hat{a}^\dagger + h.c.$$

Dark mechanical state:



?

First, we assume that the pump and probe fields are on resonance with their respective transition and second, we assume that we are in the resolved sideband regime so this corresponds to consider that this transition the width of this excited state is smaller than their spacing so in other words we can address the sideband transition individually. So you've seen in a previous video that the Hamiltonian in this case can be written in the following form where 'a' is the annihilation operators of photons in the optical cavity and 'b' is the operator of annihilation of phonon in the mechanical mode. So the first term here is the beam splitter interaction that swaps photons and phonons and these terms corresponds to the driving term due to the incoming probe field. So we have chosen here to include this as a driving term explicitly in the Hamiltonian rather than to treat it as an incoming field in the framework of input-output theory as we will do shortly. So now in close analogy with atomic EIT, we are going to look for a dark state that is a combination of the ground state that is not coupled to the excited states. So can you guess the expression of this dark states?

Notes

Summary



MECHANICAL DARK STATE ?

Hypotheses:

- Pump and probe fields on resonance with their transitions
- Resolved sideband regime $\kappa \ll \Omega_m$

Hamiltonian in the interaction picture:

$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + \sqrt{\kappa} \alpha_p \hat{a}^\dagger + h.c.$$

Dark mechanical state:

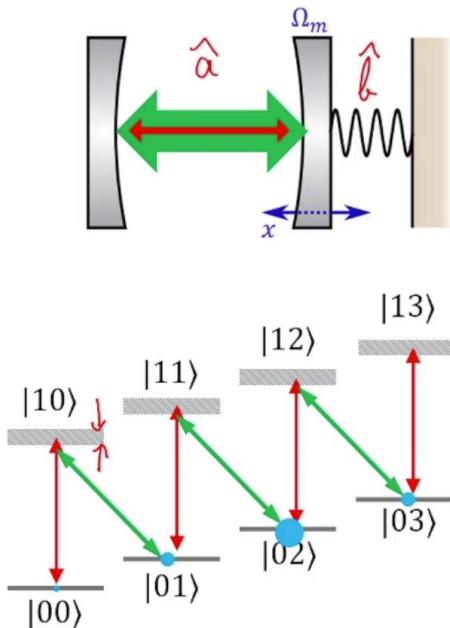
$$\hat{b}|\beta\rangle = \beta|\beta\rangle$$

$$|\Psi\rangle = |-\frac{\sqrt{\kappa}\alpha_p}{\Omega_c}\rangle$$

$$\hat{H}|\Psi\rangle = 0$$

(when cavity in $|0\rangle$)

→ The mechanical resonator rapidly **relaxes towards the dark state** $|\Psi\rangle$, preventing excitation of the cavity by the probe field.



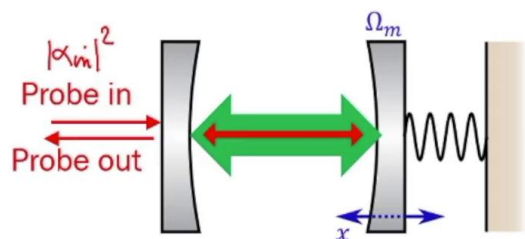
I'm going to give you a few seconds to think about this question. So to find the dark state you need to remember a very important property of coherent state namely, their eigenstate of the annihilation operator. So coherent state beta is an eigenstate with the eigenvalue beta. So you can check that the coherent state with this particular amplitude is such that $\hat{H}|\Psi\rangle = 0$, that is when the cavity is in the ground state. So in the same way as what happened with atomic EIT, the mechanical resonator will rapidly relax towards this dark state $|\Psi\rangle$ when in the presence of the two laser beam. In this case, the probe beam will not be absorbed because there is no cavity excitation.

Notes

Summary



FULL TREATMENT WITH INPUT-OUTPUT THEORY



$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + h.c.$$

Equations of motion in the interaction picture:

$$\begin{aligned}\dot{\hat{a}} &= \frac{i}{\hbar} [\hat{H}, \hat{a}] - \kappa/2 \hat{a} + \sqrt{\kappa/2} \alpha_{in} e^{-i\Omega t} \\ \dot{\hat{b}} &= \frac{i}{\hbar} [\hat{H}, \hat{b}] - \Gamma_m/2 \hat{b}\end{aligned}$$

$$\alpha_{in} \propto \sqrt{P_{in}}/\sqrt{\omega}$$

$$[\hat{a}, \hat{a}^\dagger] = 1$$

$$[\hat{H}, \hat{a}] =$$

So this dark state picture is quite useful to get a physical intuition and discuss the origin of OMIT, however, it doesn't tell us more much about the shape of the absorption spectrum, for instance or the dependence with control field amplitude. So in order to get a more quantitative description of the problem, we'll now solve the equations of motion in the framework of input-output theory. So we start from the Hamiltonian in the interaction picture. You see that we have omitted here the driving term and we have rather included the coupling to the incoming probe field within directly the Langevin equation here. So we have in this equation the field α_{in} as the dimension of square root photon per second. In other words, the incoming field has a photon flux in photon per second is given by α_{in}^2 . Finally, the factor two here has been chosen to realize the critical coupling condition for the cavity. So we can now calculate the commutators by keeping in mind that 'a' a-dagger commutator equals one. So we get 'H a'. So we get the opposite of the commutator minus $\hbar\omega_c$, sorry, 'b' and for commutator of 'H' with 'b', so be aware this time it's this Hermitian conjugate that doesn't commute with 'b' and we get minus ' $\hbar\omega_c$ a'.

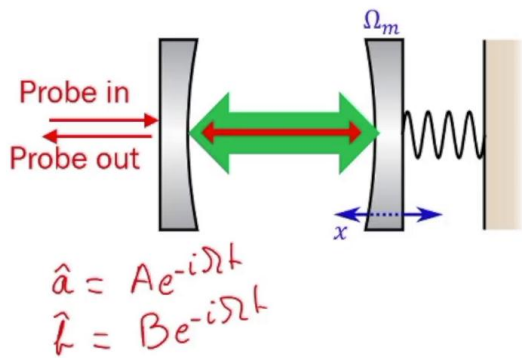
Notes

Summary



14m 46s

FULL TREATMENT WITH INPUT-OUTPUT THEORY



$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + h.c.$$

Equations of motion in the interaction picture:

$$(1) \quad \dot{\hat{a}} = -i\Omega_c \hat{b} - \kappa/2 \hat{a} + \sqrt{\kappa/2} \alpha_{in} e^{-i\Omega t}$$

$$(2) \quad \dot{\hat{b}} = -i\Omega_c \hat{a} - \Gamma_m/2 \hat{b}$$

$$(2) \Rightarrow B = \frac{-i\Omega_c A}{-i\Omega + \Gamma_m/2}$$

So we see that these equations have a single time-dependent term. Here the harmonic dependence so we will choose following and that's 'a' equals 'A' exponential minus 'i omega t' and 'b' equals 'B' exponential minus 'i omega t'. We now can solve with this ansatz. So let's start with the question two. We have 'B' equals, so 'a' here will be a source term, minus 'i omega c A' divided by so that will be because of derivative minus 'i' omega here plus gamma 'n' over two. So we see from this equation that the probe field plays actually the role of the intracavity probe field actually plays the role of a drive for the mechanical resonator. The reason for that is that the simultaneous presence of the probe and control fields inside the cavity gives rise to a bit note. In other words, the intensity inside the cavity is modulated at the difference frequency between the two beams. And so does the radiation pressure force experienced by the mirror. So the resonator gets excited when this difference gets close to the mechanical frequency within a few mechanical linewidths. That's what we see from this expression.

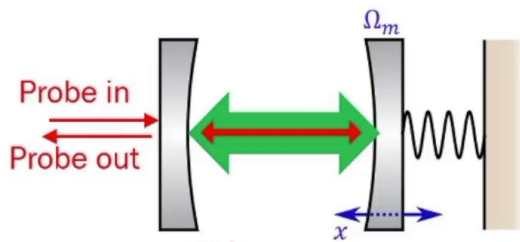
Notes

Summary



16m 49s

FULL TREATMENT WITH INPUT-OUTPUT THEORY



$$\hat{a} = A e^{-i\Omega t}$$

$$\hat{b} = B e^{-i\Omega t}$$

$$C = \frac{4\Omega_c^2}{\kappa\Gamma_n}$$

$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + h.c.$$

Equations of motion in the interaction picture:

$$(1) \quad \dot{\hat{a}} = -i\Omega_c \hat{b} - \kappa/2 \hat{a} + \sqrt{\kappa/2} \alpha_{in} e^{-i\Omega t}$$

$$(2) \quad \dot{\hat{b}} = -i\Omega_c \hat{a} - \Gamma_m/2 \hat{b}$$

$$(2) \Rightarrow B = \frac{-i\Omega_c A}{-i\Omega + \Gamma_n/2}$$

$$(1) \Rightarrow A = \frac{\sqrt{\kappa/2} \alpha_{in}}{-i\Omega + \kappa/2 + \frac{\Omega_c^2}{-i\Omega + \Gamma_n/2}}$$

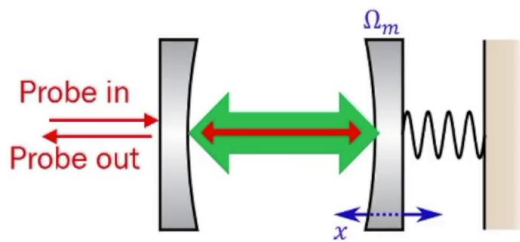
And now we also see that the mechanical amplitude is also coupled to the intracavity probe field in this equation and the reason for this is that when the mirror moves at the different frequency between the two beams, the corresponding modulation of the control beam gives rise to a sideband inside the cavity. That's perfectly superimposed with a probe beam frequency. So if we re-inject this expression inside the first equation, we get 'A' equals so everything is going to be proportional to 'A' the only source term is here so square root kappa over two alpha-in divided by so we get the derivative so minus 'i' omega here plus kappa over two. And finally, we re-inject 'b' inside this equation. So we get plus omega 'c' square over minus 'i' omega plus gamma 'n' over two. Finally, it's useful to introduce the optomechanical cooperativity four omega 'c' squared over kappa gamma 'n'. And so we get the final expression for the intracavity probe field so we divide numerator and denominator by kappa over two and we get square root two over kappa alpha-in divided by minus two 'i' omega over kappa plus one plus so we're going to get 'c' over minus two 'i' omega over gamma 'n' plus one.

Notes

Summary



FULL TREATMENT WITH INPUT-OUTPUT THEORY



Ansatz: $\hat{a} = Ae^{-i\Omega t}$
 $\hat{b} = Be^{-i\Omega t}$

Definition: $C \equiv \frac{4\Omega_c^2}{\kappa\Gamma_m}$

Input output relations
 (critical coupling):

$$\hat{a}_{out} = -\hat{a}_{in} + \sqrt{\frac{\kappa}{2}}\hat{a}$$

$$\hat{H}/\hbar = \Omega_c \hat{a}^\dagger \hat{b} + h.c.$$

Equations of motion in the interaction picture:

$$\dot{\hat{a}} = -i\Omega_c \hat{b} - \kappa/2 \hat{a} + \sqrt{\kappa/2} \alpha_{in} e^{-i\Omega t}$$

$$\dot{\hat{b}} = -i\Omega_c \hat{a} - \Gamma_m/2 \hat{b}$$

$$\Rightarrow A = \frac{\alpha_{in} \sqrt{2/\kappa}}{1 - 2i\Omega/\kappa + \frac{C}{1 - 2i\Omega/\Gamma_m}}$$

$$\Rightarrow t = \frac{\hat{a}_{out}}{\hat{a}_{in}} = \frac{1}{1 - 2i\Omega/\kappa + \frac{C}{1 - 2i\Omega/\Gamma_m}} - 1$$

So now this is the expression of the intracavity probe field as a function of the detuning omega of the injected field. And what we really care about is how much of the probe beam that's injected here will be reflected out there. And to get that we can use the input-output relation for the cavity so it's expressed again for critically coupled cavity here. And so the ratio a-out over a-in, so we calculate this from our ansatz and you see that the square root kappa over two exactly cancels square root two over kappa and so we get this final expression for the probe field transmission coefficient 't'.

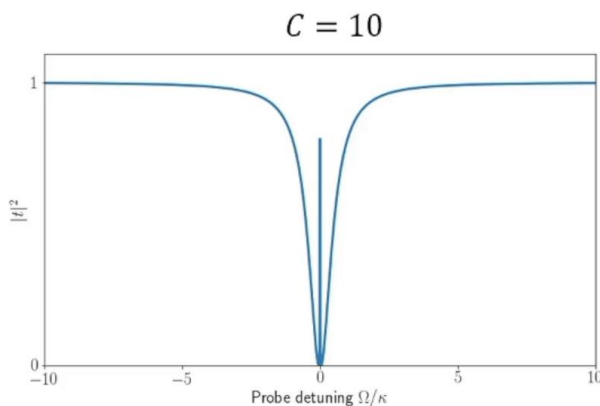
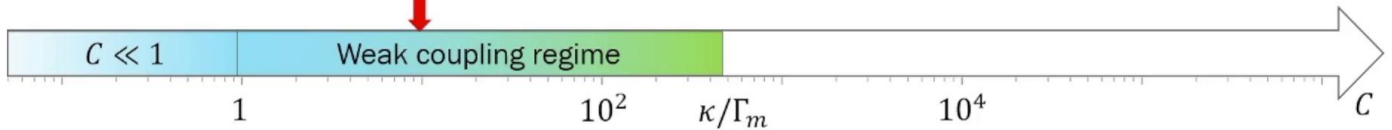
Notes

Summary



OPTOMECHANICALLY INDUCED TRANSPARENCY

$$t = \frac{1}{1 - \cancel{2i\Omega/\kappa} + \frac{C}{1 - 2i\Omega/\Gamma_m}} - 1 \quad \kappa \gg \Gamma_n$$



Weak coupling regime $\Gamma_m C \ll \kappa$

$$t \sim \frac{C}{1+C} \frac{1}{1 - \frac{2i\Omega}{\Gamma_m(1+C)}} \quad (\Omega \ll \kappa)$$

So this graph represents the modulus square of the transmission coefficient as calculated by this formula and we are now going to see how this evolve as we change the value of the cooperativity 'c'. So in an experiment this would correspond to turning up the power of the control field. So the first regime that we encounter is the one where the cooperativity is much smaller than one. In this case, this term can be neglected in the denominator and we end up with the response of a bare cavity as if it was not coupled to the mechanical resonator as we see here. So now if we crank up the power on the control field, we start to see a small transmission peak that appears here close to zero detuning. And so since this effect only occurs for detuning close to zero, we can try to get an approximate expression for the transmission around this peak and this can be obtained by neglecting this term so this is possible because kappa is usually much larger than gamma 'n'. And so in this case, you can easily check that this transmission boils down to this expression. So this is a Lorentzian of height 'c' over one plus 'c' the modulus square here and the width, this is the height and the width is given here by gamma 'n' one plus 'c'.

Notes

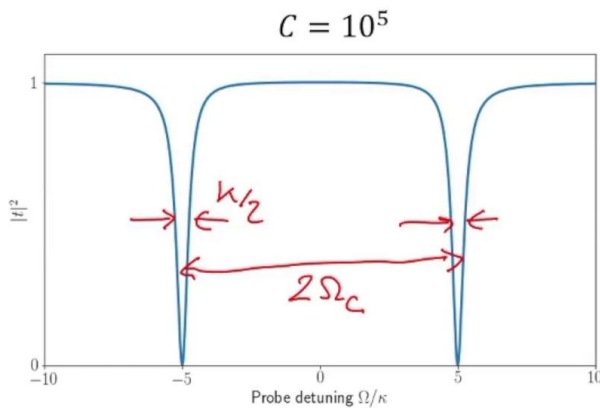
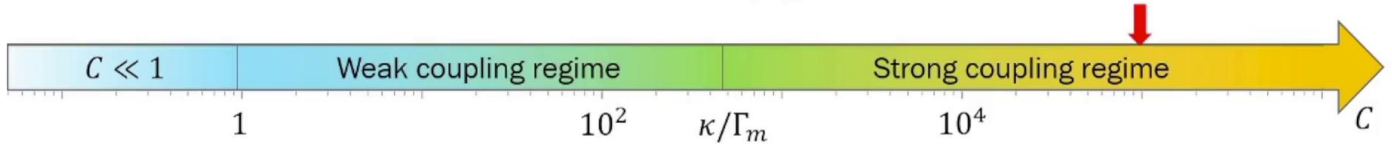
Summary



21m 17s

OPTOMECHANICALLY INDUCED TRANSPARENCY

$$t = \frac{1}{1 - 2i\Omega/\kappa + \frac{C}{1 - 2i\Omega/\Gamma_m}} - 1$$



Strong coupling regime $\Gamma_m C \ll \kappa$

$$|t|^2 \sim 1 - \frac{\kappa^2 \Omega^2}{4(\Omega_c^2 - \Omega^2)^2 + \kappa^2 \Omega^2}$$

So this linewidth is actually the total linewidth of the mechanical mode in the presence of the strong control beam that actually provides optomechanical cooling. So to summarize the requirement to observe a sizable transparency peak is as we see from this expression of this amplitude, is to have a cooperativity on the other or larger than one and this corresponds to a cooling factor by the control beam of two or more. Finally, as we increase the power of the control beam even further, the total cooling rate increases into more and it increases up to the point where basically the total mechanical linewidth gamma 'f' becomes larger than the cavity linewidth kappa. So this is the condition for strong coupling regime and you can check that the probe transmission is given in this regime by approximately this formula. This formula describes two Lorentzian peaks separated by two omega 'c' and with a width kappa over two as one would expect for normal modes that corresponds to a balanced superposition of a photonic and a phononic state.

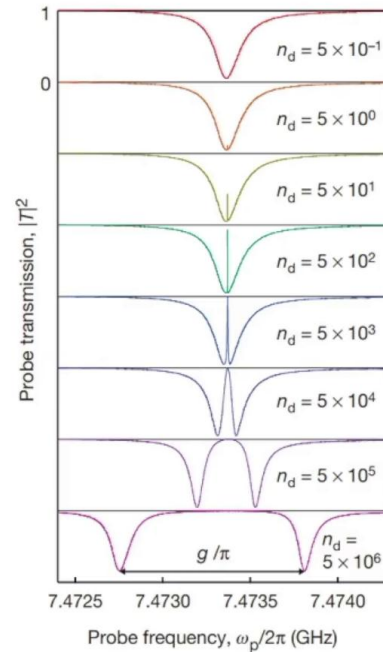
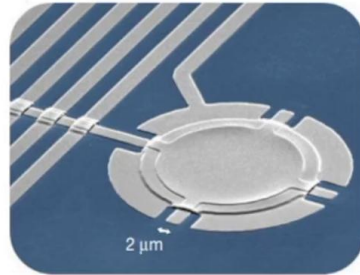
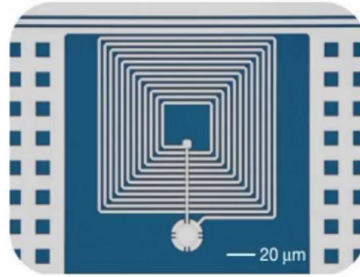
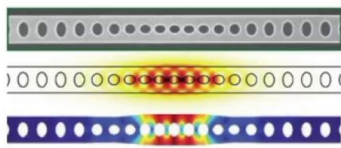
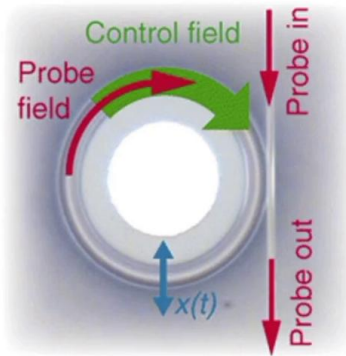
Notes

Summary



23m 15s

EXPERIMENTAL DEMONSTRATIONS



Weis, Rivière, Deléglise, Gavartin, Arcizet, Schliesser, Kippenberg, Science **330**, 1520 (2010)

Teufel, Dale Li, Allman, Cicak, Sirois, Whittaker, Simmonds, Nature **471**, (2011)

Safavi-Naeini, Mayer Alegre, Chan, Eichenfield, Winger, Lin, Hill, Chang, Painter, Nature **472** (2011)

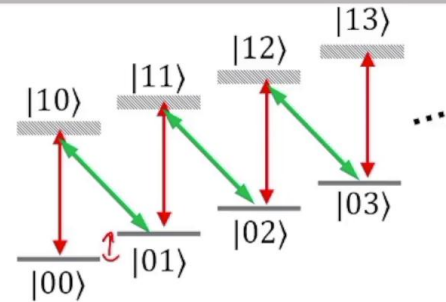
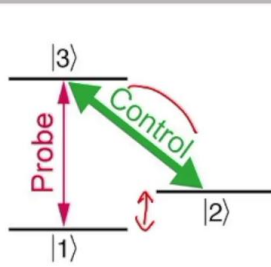
So these signatures have been observed for the first time in 2010 in a micro-toroidal cavity and shortly after this was followed by many other experimental platforms. Photonic crystal nanobeams, electromechanical system here and the experimental data that you see here were obtained in this last experimental in this last electromechanical system in Bohler.

Notes

Summary



COMPARISON EIT/OMIT



Atomic EIT	OMIT
Electronic interference	Optical interference
Coherence 1-3	Intracavity probe field amplitude A
Coherence 1-2	Mechanical oscillation amplitude B
Ground state level splitting	Phonon energy
Rabi frequency	Optomechanical coupling rate $\Omega_c = 2g_0\sqrt{n}$

So we can now examine the precise analogy between EIT and OMIT. Both of these phenomena are due to an interference between two excitation pathway. They differ by the nature of the state that interfere. In atomic EIT, the amplitude properties for electronic states are interfering whereas in OMIT, interference occurs between different optical fields. However, there's a direct correspondence in the underlying mathematical formalism. For instance, the coherence between in the one-three transition and one-two transition in atomic EIT corresponds directly to the intracavity probe field amplitude 'A' and mechanical oscillation amplitude 'B'. The ground state level splitting here corresponds to the mechanical frequency. And finally, the Rabi frequency of the control field is equivalent to the generalized optomechanical coupling rate omega 'c'.

Notes

Summary



25m 25s

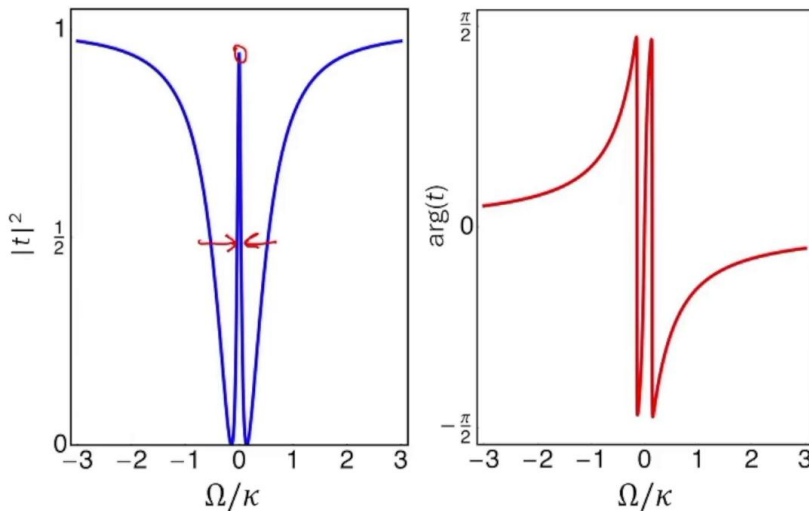
SLOW LIGHT

$$t \sim \frac{C}{1+C} \frac{1}{1 - 2i\Omega/\Gamma_m(C+1)}$$

Group delay for a pulse centered in the OMIT window

$$\tau_g = \left. \frac{d\phi}{d\Omega} \right|_{\Omega=0} = \frac{2}{\Gamma_n(C+1)}$$

$$\tan(\phi) = \frac{2\Omega}{\Gamma_n(C+1)}$$



So in close analogy with EIT the probe beam also undergoes a strong dispersion as it is transmitted through a transparency window. This is what we see when we look here at the phase the argument of this complex transmission coefficient as a function of probe detuning. So this can be quantified by calculating the group delay which represents the delay that the envelope of a shot light pulse will undergo as it propagates across the system. So if we take the approximate formula that is written here in the weak coupling regime, we can calculate the tangent of this complex argument, tangent phi equals two omega divided by gamma 'n' 'c' plus one. And so we can calculate this group velocity at the maximum of transmission here in omega equal zero and so this is two divided by gamma 'n' 'c' plus one. Now we need to compare this time delay to another relevant quantity and which will be here the inverse of the bandwidth of this transparency window. So this time because this is it has dimension of a time, tau 'n' equals one over gamma 'n' 'c' plus one corresponds to the minimum duration of a pulse whose spectrum would fit within the transparency window.

Notes

Summary



SLOW LIGHT

$$t \sim \frac{C}{1+C} \frac{1}{1 - 2i\Omega/\Gamma_m(C+1)}$$

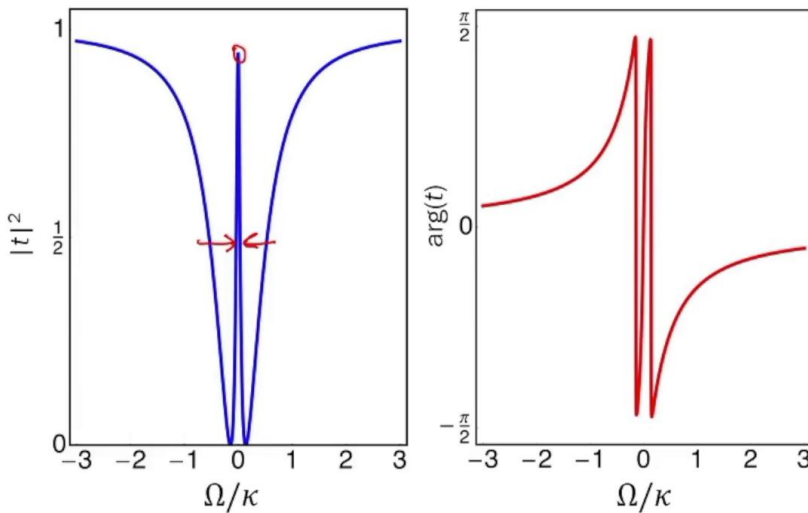
Group delay for a pulse centered in the OMIT window

$$\tau_g = \left. \frac{d\phi}{d\Omega} \right|_{\Omega=0} = \frac{2}{\Gamma_n(C+1)}$$

$$\tan(\phi) = \frac{2\Omega}{\Gamma_n(C+1)}$$

$$\tau_n = \frac{1}{\Gamma_n(C+1)}$$

→ Delay-bandwidth product ≈ 2



In other words, the delay bandwidth product that we calculate to be two here means that a single optomechanical system cannot delay a pulse by more than twice its duration. However, by tuning in 'c' two, the control field while the pulse is interacting with the optomechanical system, we can show that it's possible to map a given propagating mode onto the mechanical state, that is, to store the amplitude, the phase and even possibly the quantum state of the pulse into static mechanical oscillation.

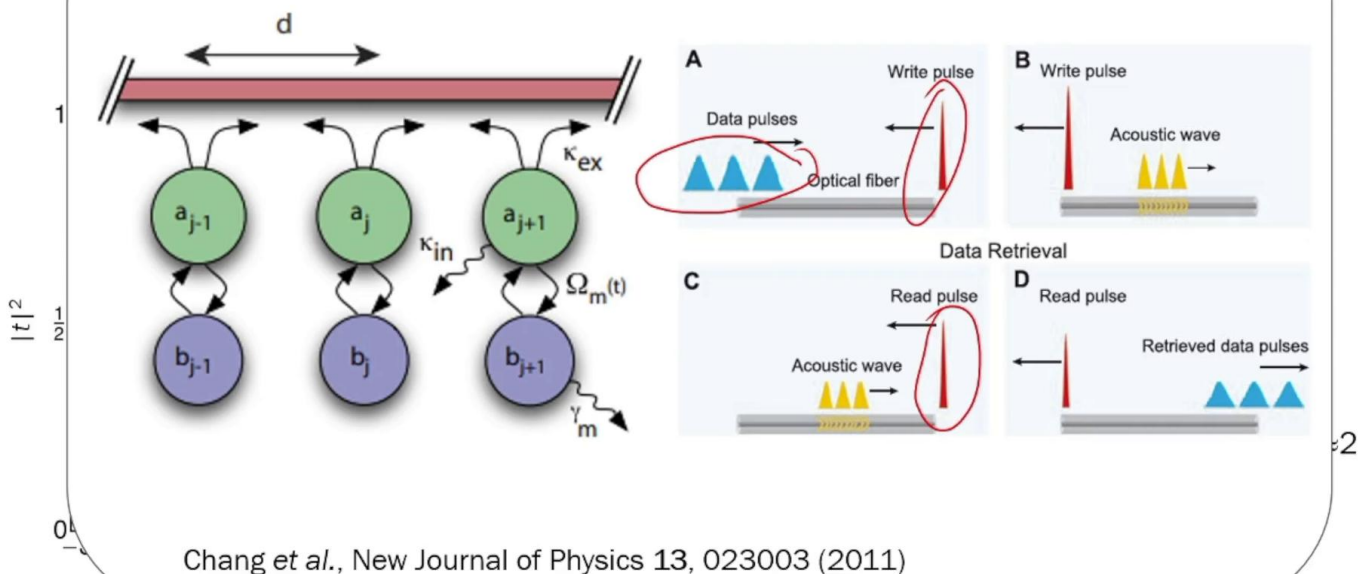
Notes

Summary



SLOW LIGHT

Storing arbitrary pulses of light in an optomechanical array



It was even proposed to stir it around pulses arriving in an unknown temporal mode, as we see here in arbitrary temporal mode, by adiabatically slowing them down while they are propagating within an optomechanical array. So they could be stored inside coherent mechanical oscillations by at first, writing pulse here and retrieved later on after an arbitrary delay time by a second readout pulse. Here the data pulses are close to the probe transition frequency while the write pulse and readout pulse corresponds to light at the control frequency.

Notes

Summary



CONTROLLING LIGHT WITH LIGHT AT LOW POWER

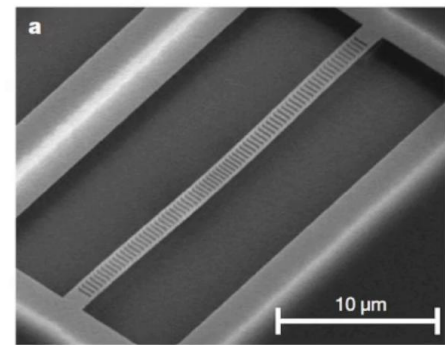
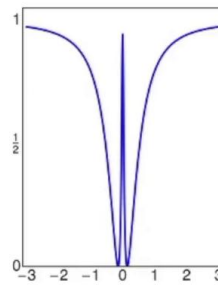
Transmission on resonance

$$t_0 = \frac{C}{C+1} = \frac{C_0 n}{C_0 n + 1}$$

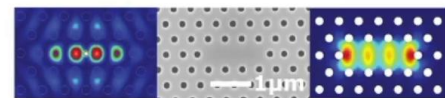
Single photon cooperativity $C_0 = \frac{4g_0^2}{\kappa\Gamma_m}$

Number of photons to achieve $t_0 = 1/2$: $n = 1/C_0$

System	n
Silica microtoroids	1000
Microwave electromechanics	100
Integrated nano-optomechanics	10



*Eichenfield et al. Nature **462**, 78 (2009)



Gavartin et al. PRL **462**, 78 (2009)

Finally, OMIT can be seen as the optical equivalent of a transistor where a beam of light influences the transmission of a second beam. It is not obviously difficult to generate such photon-photon interactions, especially at the single photon level. So how many photons are required to switch the probe beam on or off? This can be calculated to be the inverse of the single photon cooperativity, which is the value of the cooperativity when the interactivity control field is in a single photon coherent state. Thanks to this figure of merit, we can now compare values of the mechanical platform. So in the optimized silica microtoroid that were developed in this work, for instance, approximately a thousand photons were required to observe the onset of an image. This figure of merit is typically an order of magnitude better with microwave electromechanical systems. And thanks to the very strong confinement of photonic and phononic modes in a small volume, integrated nanophotonic systems perform even better. Finally, the single photon cooperativity close to one was recently demonstrated in the group of Tobias Kippenberg with evanescently coupled nanobeams.

Notes

Summary



29m 54s

CONTROLLING LIGHT WITH LIGHT AT LOW POWER

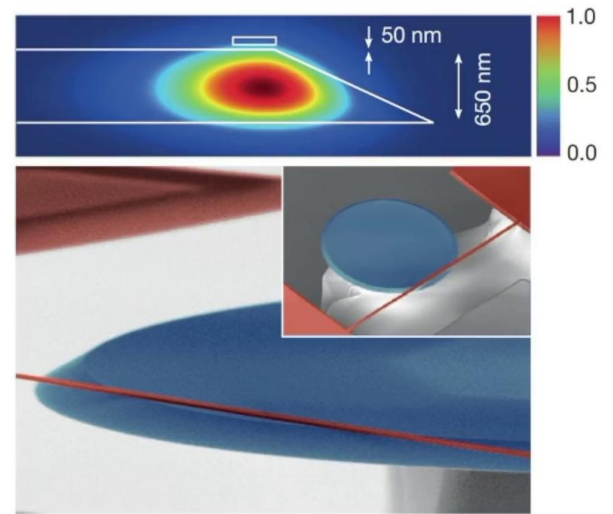
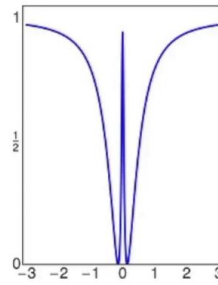
Transmission on resonance

$$t_0 = \frac{C}{C+1} = \frac{C_0 n}{C_0 n + 1}$$

Single photon cooperativity $C_0 = \frac{4g_0^2}{\kappa\Gamma_m}$

Number of photons to achieve $t_0 = 1/2$: $n = 1/C_0$

System	n
Silica microtoroids	1000
Microwave electromechanics	100
Integrated nano-optomechanics	10
Silicon-Nitride nanobeam	1



D. J. Wilson, V. Sudhir, N. Piro, R. Schilling, A. Ghadimi, T. J. Kippenberg Nature 524 (2015)

In other words, in such a system the very large coupling between the motion of the nanobeam located few tens of nanometer above an optical mode together with the very long currents time of the mechanical resonators might allow to realize a phonon mediated photon-photon interaction at the single photon level. Now it is time to summarize what we've learned about during this lesson.

Notes

Summary

31m 11s



CONCLUSION / SUMMARY

- EIT is an interference effect in a 3-level atom
- An analogous phenomenon exists in cavity Optomechanics

OMIT could enable:

- Switching at ultralow light level
- Pulse delay
- Light storage

So EIT is an interference effect in a 3-level atom that can prevent the atom from getting excited and we have seen that OMIT is a very analogous phenomenon that occurs in a cavity optomechanical set up. OMIT could enable switching light beam with another light beam at very low light power realizing delay lines for optical pulses or even light storage inside long live mechanical vibration. Thank you for your attention.

Notes

Summary



31m 39s