Induced Transparency in Hybrid Opto-Mechanical Systems

Dr. Farhan Saif

Department of Electronics, Quaid-i-Azam University,
Islamabad, Pakistan

Department of Engineering sciences, University of Electro Communications,
Chofu, Tokyo, Japan

Summer School on New Advances in Quantum Information Science
and Quantum Technologies
SamarKand, Uzbekistan

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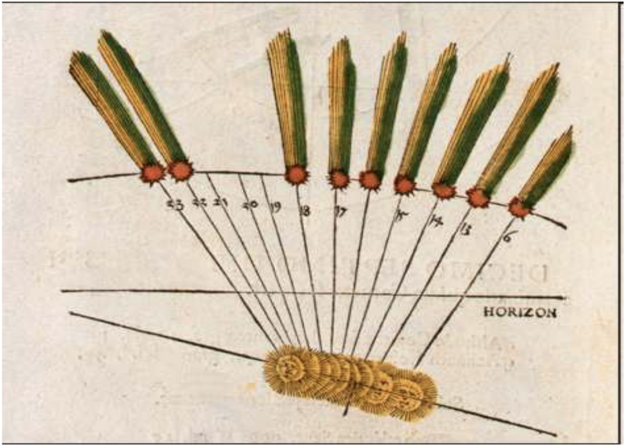
Outline

AlHazan (Ibn Al Hasham) (1139) - Vision

Peter Arpian (1577) - Comet tail observation



Peter Arpian « Astronomicum Caesareum » (1577)

Radiation Energy

Jules Verne, in 'From the Earth to the Moon', published in 1865, wrote "there will some day appear velocities far greater than these [of the planets and the projectile], of which light or electricity will probably be the mechanical agent ... we shall one day travel to the moon, the planets, and the stars." This is possibly the first published recognition that light could even move ships through space.

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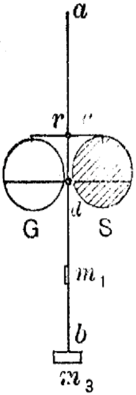
Ernest Nichols and Gordon Hull conducted a similar independent experiment in 1901 using a Nichols radiometer.

Nichols and Hull,1901 Lebedev, 1901

A PRELIMINARY COMMUNICATION ON THE PRESSURE OF HEAT AND LIGHT RADIATION.

BY E. F. NICHOLS AND G. F. HULL.

MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume."



$$\boxed{F = 2 \times \frac{I}{c}}$$

Nichols and Hull,Physical Review **13**,307 (1901)

Svante Arrhenius predicted in 1908 the possibility of solar radiation pressure distributing life spores across interstellar distances, providing one means to explain the concept of panspermia. He apparently was the first scientist to state that light could move objects between stars.

Konstantin Tsiolkovsky first proposed using the pressure of sunlight to propel spacecraft through space and suggested, "using tremendous mirrors of very thin sheets to utilize the pressure of sunlight to attain cosmic velocities".

Friedrich Zander (Tsander) published a technical paper in 1925 that included technical analysis of solar sailing. Zander wrote of "applying small forces" using "light pressure or transmission of light energy to distances by means of very thin mirrors".

Example of comet tail
composed of particles radius r

- $I = 1$ kWatt / m^2 (cf Sun radiation at Earth)
  - opaque particle diameter ~ 1μm, mass ~ 10^{-15} kg, surface ~ 10^{-12} m^2
  - then P intercepted ~ 10^{-9} Watt
    hence F ~ 3,3 10^{-18} Newton *comparable to gravitational attraction force of the sun at Earth-Sun distance*

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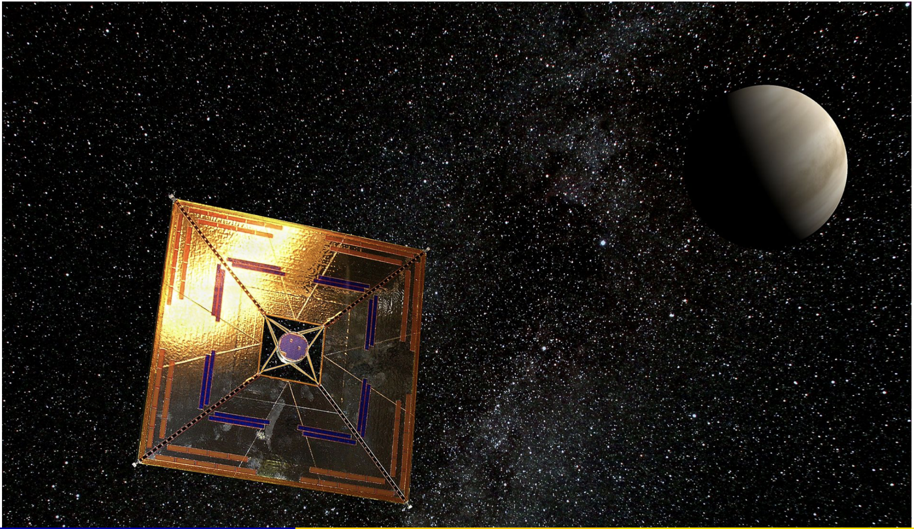
Force of gravity due to earth on the dust particle is

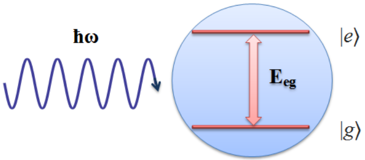
$$F = mg = 10^{-14} Newton$$

Hubbel Telescope - Nebula

IKAROS - Interplanetary Kite Accelerated by Radiation Of the Sun (2010)- Japan Aerospace Exploration Agency



Optical Force on Atom



In dispersive regime the atom interacts with the atoms

$$H_{\text{eff}} \equiv \frac{\hat{\mathbf{p}}^2}{2m} + \frac{\hbar\Omega_R^2}{\Delta} u^2(\hat{\mathbf{r}}).$$

Optical Force on Atom

That introduces position dependent optical force on atoms

$$F_{rp} = -\frac{\hbar\Omega_R^2}{\Delta} u(\hat{\mathbf{r}})\nabla u(\hat{\mathbf{r}}).$$

which is attractive or repulsive since

$$\Delta = \omega - \omega_{eg}$$

Optical Tweezers

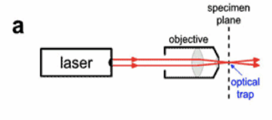
Optical Tweezers

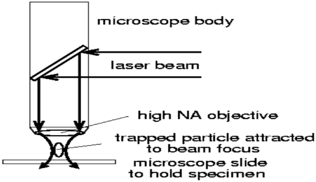
VOLUME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

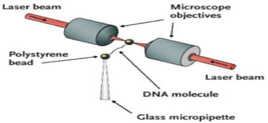
A. Ashkin
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 3 December 1969)

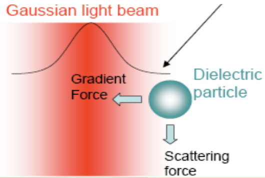
Single beam optical tweezers



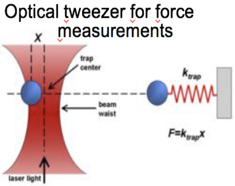


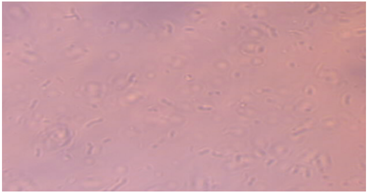
Dual beam optical tweezers





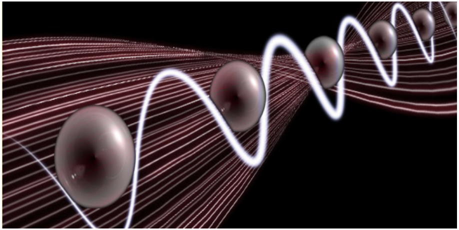
Optical Tweezers — Applications

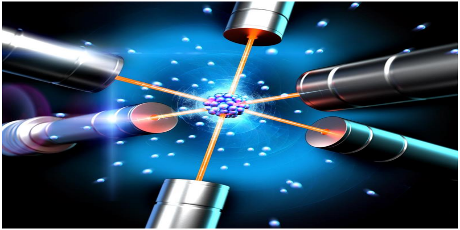


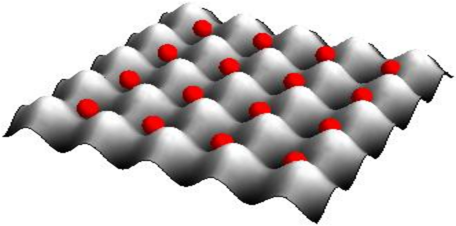


Hold, apply a force, measure force, local viscosity
holding and trapping atom, molecules and nano-particles
force measurement of cell structures and DNA coiling in pico newton range
elasticity measurement of DNA

Trapping plus Cooling

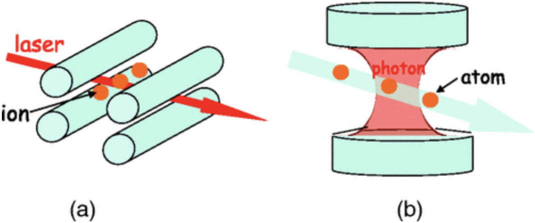






Nobel Prize (1997)
William Daniel Phillips
Claude Cohen-Tannoudji
Steven Chu

Novel interactions between Light and Matter

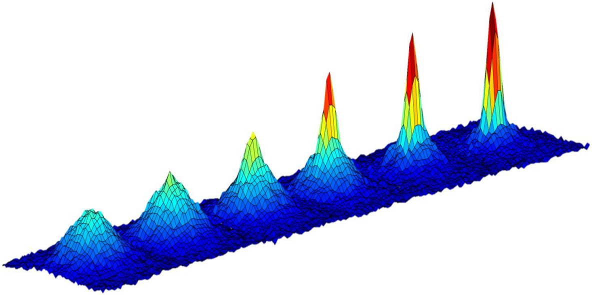


Nobel Prize (2012)

Serge Haroche, David Wineland

Possible to trap single atom and single photon

Bose Einstein Condensation



Nobel Prize (2001)

Carl Wieman, Wolfgang Ketterle, Eric Allin Cornell

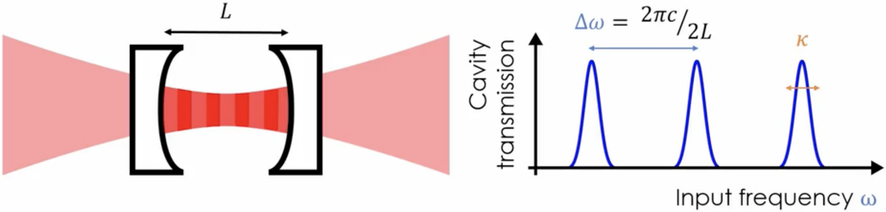
D. Becker *et. al.*, Nature, volume 562, October 18, pages391–395 (2018)

OPTICAL FORCE AT MACROSCOPIC SCALE

Radiation Pressure Force + Optical Cavity

Optical Cavity

Optical cavities can be used to engineer a resonance (enhancement) at a chosen wavelength.



$$L = j\frac{\lambda}{2} \qquad \omega_j = j\frac{\pi c}{L}$$

Optical Cavity with Radiation Pressure Force

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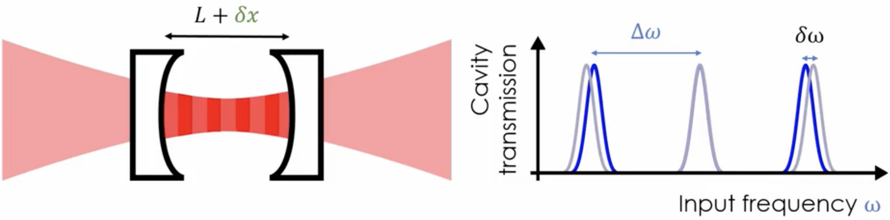


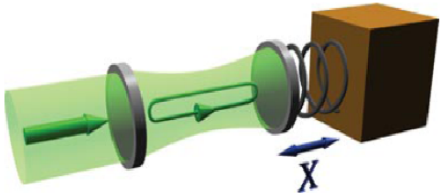
You get a frequency shift of: $\delta\omega = {}^{\delta x}/_{\lambda/2} \times \Delta\omega$ or

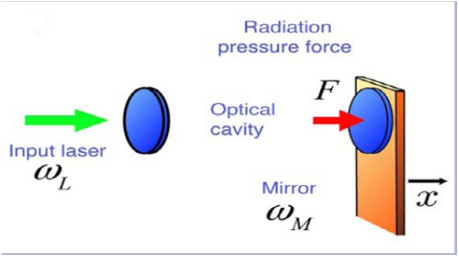
$$G = {}^{\delta\omega}/_{\delta x} = \frac{\omega}{L}$$

$$\omega(\delta x) = \frac{\pi c}{L + \delta x} \approx \omega - \frac{\omega}{L}\delta x$$

LIGHT Induced Mechanics — Opto Mechanics

In opto-mechanical resonators, an optical mode couples to mechanical vibrations via radiation pressure induced by circulating optical fields. The cavity (a.k.a. Fabry-Pérot cavity) consists of a highly reflective fixed input mirror and a small movable end mirror harmonically coupled to a support that acts as a thermal reservoir.





a) Eventually light comes in the cavity and *exerts a force* on the mirror to displace it

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b) As it changes the *position*, the amount of radiations in the cavity changes, that is a back action of the mirror
c) The position of the *mirror changes* and varies the radiation pressure force, thus introducing the cavity effect as it modifies the radiation pressure force
d) Hence the radiation pressure force and resultant movement of mirror acts as nonlinearity for the electromagnetic field. Thus we *simulate* nonlinearity of the medium as a field observes while interacting with a medium.

Radiation Pressure Force

A photon carries momentum of amount $\hbar k$, where $k = 2\pi/\lambda$. The photon interacts and imparts its momentum to the end-mirror. Hence, a change in the momentum of the mirror

$$\Delta p = \frac{2E}{c},$$

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$$\Delta p = \frac{2E}{c} ,$$

here E is the energy of the photon. If the round trip time of a photon is $\Delta t = 2L/c$, the radiation pressure force F_{RP} exerted by n photons on the mirror is,

$$F_{RP} = n\frac{\Delta p}{\Delta t} = n\frac{E}{L} .$$

Radiation Pressure Potential

The corresponding potential V_{RP} due to mirror displacement is expressed by continuous variable $\delta x = q_m$ is,

$$V_{RP}(q_m) = -n\frac{E}{L}q_m.$$

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Quantum mechanical description of the potential is obtained by replacing c-number representation by respective operators, such that, $\hat{q}_m$ and $\hat{n} = \hat{a}^\dagger \hat{a}$. As we consider the energy of the cavity photon as $E = \hbar\omega_c$, the quantum mechanical expression of the potential experienced by the mirror becomes,

$$\hat{V}_{RP} = -\hbar\frac{\omega_c}{L}\hat{a}^\dagger \hat{a}\hat{q_m}\,.$$

Hamiltonian of Opto-Mechanical System

We write the opto-mechanical Hamiltonian of the system $\hat{H}_o$ as,

$$\hat{H}_o = \hat{H}_C + \hat{H}_M + \hat{H}_{CM} + \hat{H}_{CL}.$$

$$\hat{H}_o = \hbar\omega_c \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right) + \hat{H}_M + \hat{H}_{CM} + \hat{H}_{CL}.$$

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$$\begin{aligned} \hat{H}_o &= \hbar\omega_c \left(\hat{a}^\dagger \hat{a} + \frac{1}{2}\right) + \left(\frac{\hat{p'}^2}{2M} + \frac{1}{2} M\omega_m^2 \hat{q}_m^2\right) \\ &+ \hat{H}_{CM} + \hat{H}_{CL}. \end{aligned}$$

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where

$$|E_L| = \sqrt{\frac{2\kappa P_l}{\hbar\omega_l}}.$$

Transformed Hamiltonian

$$\hat{U}(t) = e^{i\omega_l t \hat{a}^\dagger \hat{a}}.$$

The system Hamiltonian, H_o, therefore attains the shape of a time-independent transformed Hamiltonian $\hat{H}_m$, that is

$$\hat{H}_m = \hbar\Delta_c \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_m}{2}(\hat{q}^2 + \hat{p}^2) - \hbar\xi\hat{q}\hat{a}^\dagger\hat{a} + i\hbar E_L(\hat{a}^\dagger + \hat{a}).$$

Here, Δ_c is the difference of cavity frequency and laser frequency i.e.

$$\Delta_c = \omega_c - \omega_l.$$

The gravitational wave detector - LIGO & Advanced VIRGO

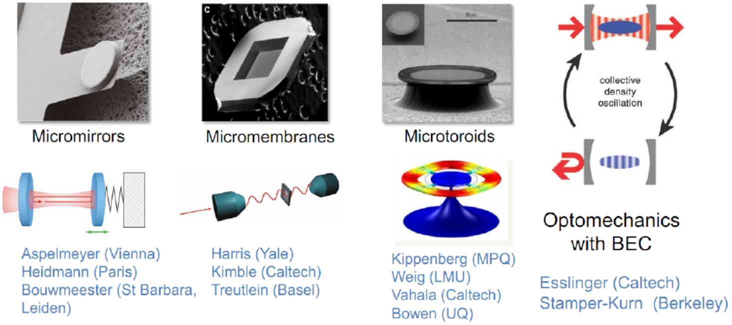
Applications in LIGO:
the Laser Interferometer Gravitational-wave Observatory, seeks to detect gravitational waves -- ripples in the fabric of space-time.
operated by Caltech & MIT:::supported by the National Science Foundation.

Nobel Prize 2017

Rainer Weiss Barry C. Barish and Kip S. Thorne

Cavity opto-mechanics - an excellent playground

Owing to the recent theoretical as well as experimental advancements over the past few years, the field of cavity optomechanics has cemented its place in the present-day photonic technology.



The Model

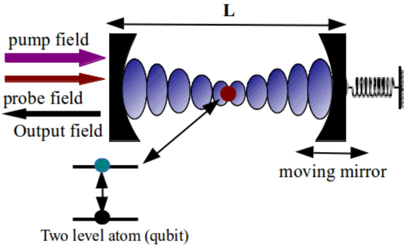


Figure: The schematic representation for the hybrid optomechanical system. A high Q Fabry-Pérot cavity of length L consists of a fixed mirror, a movable mirror and a two-level atom. The cavity is simultaneously driven by a strong pump field of frequency ω_l and a weak probe field of frequency ω_p.

The Model

Under the rotating reference frame at the frequency ω_l of the strong driving field, the total Hamiltonian of the system can be written as

$$H_T = H_o + H_a + H_{int} + H_p,$$

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$$H_{int} = \hbar g_{ac}(c^\dagger \sigma_+ + c\sigma_-),,$$

$$H_p = i\hbar(E_p e^{-i\delta t} c^\dagger - E_p^* e^{i\delta t} c),.$$

where $\Delta_a = \omega_a - \omega_l$, $\delta = \omega_p - \omega_l$ and $|E_p| = \sqrt{\dfrac{2\kappa P_p}{\hbar \omega_p}}$.

Mean field approximation

Using the mean field approximation [1,2], i.e. $\langle qc \rangle \simeq \langle q \rangle \langle c \rangle$, the mean value equations can be written as:

$$
\begin{aligned}
\frac{d\langle p \rangle}{dt} &= -m\omega_m^2 \langle q \rangle - \gamma_m \langle p \rangle + g_{mc} \langle c^\dagger \rangle \langle c \rangle, \\
\frac{d\langle q \rangle}{dt} &= \frac{\langle p \rangle}{m}, \\
\frac{d\langle c \rangle}{dt} &= -(\kappa + i\Delta_c)\langle c \rangle + ig_{mc}\langle c \rangle \langle q \rangle - ig_{ac}\langle \sigma_- \rangle \\
&\quad + E_L + E_p e^{-i\delta t}, \\
\frac{d\langle \sigma_- \rangle}{dt} &= -(\gamma_a + i\Delta_a)\langle \sigma_- \rangle + ig_{ac}\langle c \rangle \langle \sigma_z \rangle.
\end{aligned}
$$

1

[1] [1] M. J. Akram, F. Ghafoor and F. Saif, J. Phys. B: At. Mol. Opt. Phys. (Feb, 2015).
[2] G. S. Agarwal and S. Huang, Phys. Rev. A 81, 041803(R) (2010).

mean response of the system

In order to obtain the steady-state solutions, we make the ansatz

$$\langle h\rangle = h_s + h_- e^{-i\delta t} + h_+ e^{i\delta t},$$

[2] (R. W. Boyd, *Nonlinear Optics*, acad. press, New York, 2010)

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$$c_s = \frac{E_L}{\kappa + i\Delta - \frac{g_{ac}^2 \langle \sigma_z \rangle_{ss}}{\gamma_a + i\Delta_a}},$$

$$c_- = \frac{E_p(A-B)}{BB' + (A-C)(A'+C) - (AB' + A'B) + 2iC\Delta},$$

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where, $A = \kappa - i\Delta_c - i\Delta + \frac{ig_{mc}^2}{m\hbar(\omega_m^2 - i\gamma_m\Delta - \Delta^2)}|c_s|^2$, $B = \frac{g_{ac}^2\langle\sigma_z\rangle_{ss}}{\gamma_a - i\Delta_a - i\Delta}$,

$C = \frac{ig_{mc}^2}{m\hbar(\omega_m^2 - i\gamma_m\Delta - \Delta^2)}|c_s|^2$, $\quad \Delta = \Delta_c - \frac{g_{mc}^2}{m\hbar\omega_m^2}|c_s|^2$. [2]

[2] (R. W. Boyd, *Nonlinear Optics*, acad. press, New York, 2010)

Input-Output Thoery

In order to investigate the optical properties of the output field, we employ the standard input-output relation

$$c_{out}(t) = c_{in}(t) - \sqrt{2\kappa} c(t)$$

where c_{in} and c_{out} are the input and output operators, respectively. By using the input-output relation and the ansatz shown in Eq. (1) for $\langle c(t) \rangle$, we can obtain the expectation value of the output field as,

$$\begin{aligned} \langle c_{out}(t) \rangle &= (E_L - \sqrt{2\kappa} c_s) + (E_p - \sqrt{2\kappa} c_-) e^{-i\delta t} \\ &- \sqrt{2\kappa} c_+ e^{i\delta t}. \end{aligned}$$

3

[3] (Walls & Milburn, *Quantum Optics*)

The probe Transmission, Phase & Group Delay

The transmission of the probe field, which is the ratio of the returned probe field from the coupling system divided by the sent probe field [3], can be acquired as

$$T(\omega_p) = \frac{E_p - \sqrt{2\kappa} c_-}{E_p} = 1 - \frac{\sqrt{2\kappa} c_-}{E_p}.$$

For an optomechanical system, in the region of the narrow transparency window the rapid phase dispersion, viz. $\phi_t(\omega_p) = arg[T(\omega_p)]$, causes the transmission group delay,

$$\tau_g = \frac{d\phi_t(\omega_p)}{d\omega_p} = \frac{d\{arg[T(\omega_p)]\}}{d\omega_p}.$$

4

4 [3] A. H. Safavi-Naeini, T. P. Alegre, J. Chan, M. Eichenfield, M. Winger, Q. Lin, J. T. Hill, D. E. Chang, and O. Painter, Nature (London) **472**, 69 (2011).

Mechanically Induced Transparency

In order to quantify the fast and slow light effects, we consider experimentally realizable parametric values of the optomechanical system in our numerical simulations [4,5]:

$\omega_m/2\pi = 10$ MHz, $E_L/2\pi = 2$ MHz, $\Delta_c/2\pi = 10$ MHz,
$\Delta_a/2\pi = \pm 10$ MHz, $g_{mc}/2\pi = 1.2$ MHz, $g_{ac}/2\pi = 4$ MHz,
$\kappa/2\pi = 215$ KHz, $\gamma_a/2\pi = 200$ KHz, and, $\gamma_m/2\pi = 140$ Hz.

Note that $\omega_m > \kappa$, therefore, the system operates in the resolved-sideband regime, also termed as good-cavity limit.
[5]

[5][4] S. Grolacher, K. Hammerer, M. R. Vanner and M. Aspelmeyer, Nature **460**, 724 (2009).
[5] M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, Rev. Mod. Phys. **86**, 1391 (2014).

The probe transmission: ($g_{mc} \neq 0$, $g_{ac} = 0$)

We consider the case when atom-field coupling is switched off, i.e. $g_{ac} = 0$, this reduces the system to a single-ended optomechanical system.

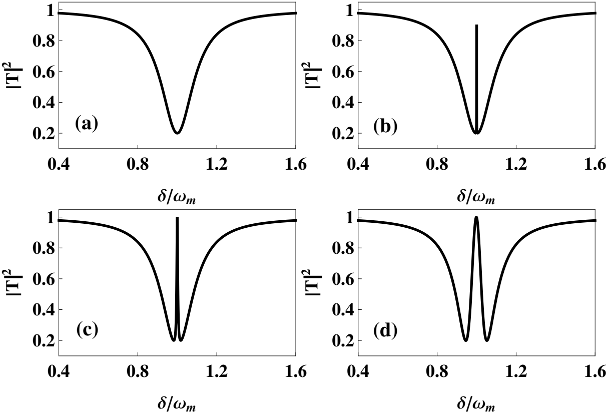


Fig. (2): The transmission $|T|^2$ vs δ/ω_m for $g_{mc}/2\pi$ =0, 0.5, 0.8, 1.2 MHz, (a) to (d), respectively.

Super-Luminality or Fast light ($g_{mc} \neq 0$, $g_{ac} = 0$)

We consider the case when atom-field coupling is switched off, i.e. $g_{ac} = 0$, this reduces the system to a single-ended optomechanical system.

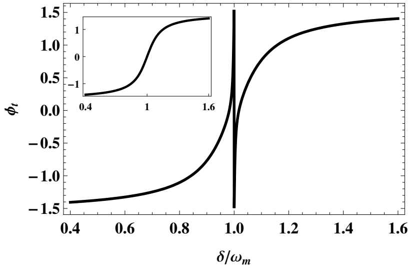


Fig. (3): The phase ϕ_t vs δ/ω_m. We observe rapid phase dispersion!

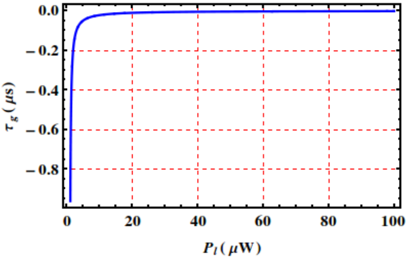


Fig. (4): Group delay (τ_g) as a function of the pump power P_l. **Fast Light!**

Fast Light in hybrid optomechanics

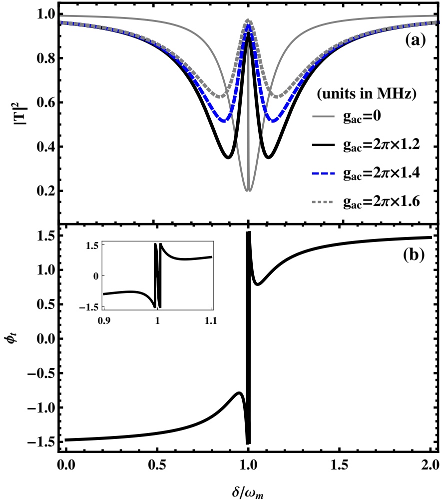
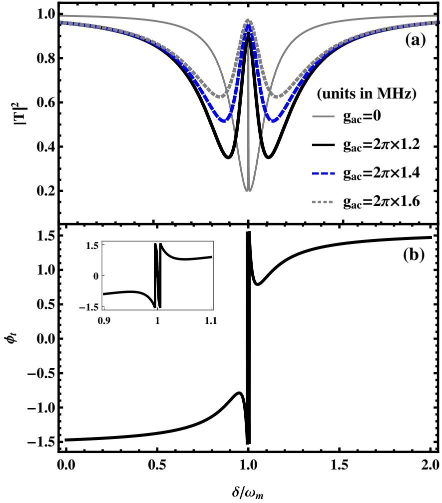


Fig. (5): (a) The transmission $|T|^2$ vs δ/ω_m. (b) The pase ϕ_t vs δ/ω_m for $g_{ac}/2\pi = 1.2$ MHz.

Fast Light in hybrid optomechanics



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- The characteristics of the probe field changes in the presence of g_{ac}.

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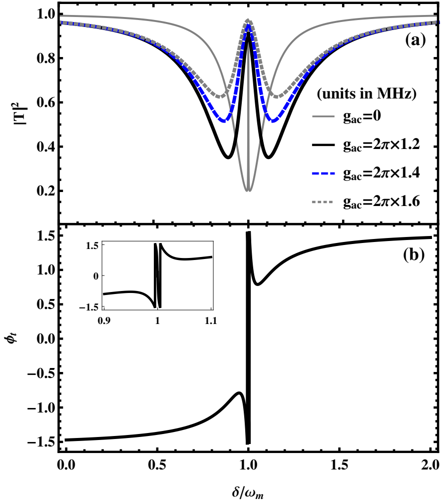

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- The characteristics of the probe field changes in the presence of g_{ac}.
- As compared with previous case, due to the presence of atomic-ensemble, more rapid phase change occurs!

Enhancement of Fast Light

We obtain the pulse advancement of the order 1.2 *ns* for $g_{ac} = 2\pi \times 4$ MHz, and 20 *ns* for $g_{ac} = 2\pi \times 8$ MHz.

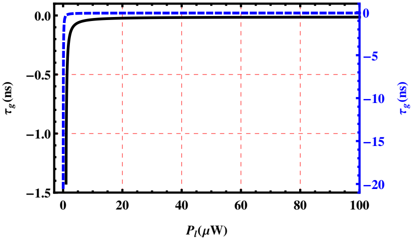

Fig. (6): Group delay τ_g vs p_l for $\delta = \omega_m$ and $\Delta_a = \omega_m$, is shown for atom-field coupling $g_{ac}/2\pi = 4$ (black-solid curve) and 8 MHz (blue-dashed curves), respectively.

From Fast to Slow light

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- However, in optomechanics, no switching mechanism has been reported before!

From Fast Light to Slow Light

In our scheme, change in the atomic detuning from $\Delta_a = \omega_m$ to $\Delta_a = -\omega_m$, acts as a tunable switch from fast-light to slow-light. The atomic detuning $\Delta_a = -\omega_m$ means that the atomic ensemble is resonant with the Stokes sideband.

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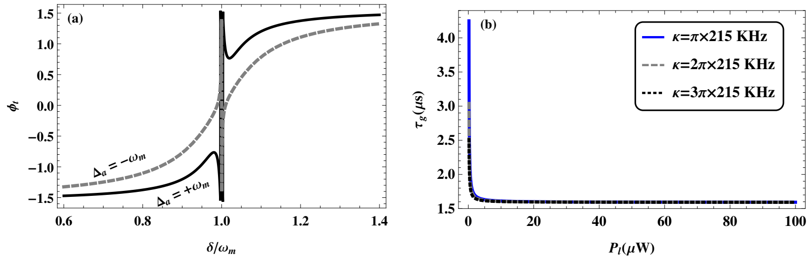

Fig. (7): (a) Phase ϕ_t vs δ/ω_m, for $\Delta_a = \omega_m$ and $\Delta_a = -\omega_m$. (b) τ_g vs P_l for $\Delta_a = -\omega_m$.

Conclusions

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- We show fast & slow light effects of the transmitted probe field in a hybrid OMS with a single two-atom for suitable parametric regimes.
- It is shown that the addition of a two-level atom in the system, not only affects the transmission of the probe field, but also yields the high phase dispersion, which makes it possible to realize the enhancement of fast light.
- In addition, a tunable switch from fast to slow light is achievable in our model by adjusting the atomic-detuning as $\Delta_a = \pm\omega_m$.

Conclusion

- This technique has potential applications for designing novel quantum-information-processing gates, delay lines & optical buffers for telecommunication systems, as well as the relevant applications in present-day photonic technology.

previous schemes vs our scheme

The Model	Fast Light	Slow Light	Tunable Switch	Reported by
single-ended OMS	✔	✘	✘	D. Tarhan, Act. Phys. Pol. A. 124, 46 (2013). D. Tarhan *et al.* Phys. Rev. A 85, 12345 (2013).
quadratically coupled OMS	✘	✔	✘	X-G Zhan *et al.* J. Phys. B: At. Mol. Opt. Phys. 46, 025501 (2013).
Hybrid BEC- OMS	✘	✔	✘	B. Chen, C. Jiang, and K. D. Zhu, Phys. Rev. A 83, 055803 (2011).
Hybrid two-mode OMS	✘	✔	✘	C. Jiang, H. Liu, Y. Cui, X. Li, G. Chen & B. Chen, Opt. Express 21, 12165 (2013).
Hybrid QED-OMS (our model)	✔	✔	✔	M. J. Akram & F. Saif, Phys. Rev. A. (in process), arXiv:1501.06062, (2015)

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THANKS