OPTOMEKANİK SİSTEMLERDE KUANTUM OPTİK UYGULAMALARI

Devrim Tarhan

Kobit 1 2-3 Şubat 2017

Teşekkür

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- *Doç. Dr. M. Emre Taşgın, Hacettepe University, Turkey*
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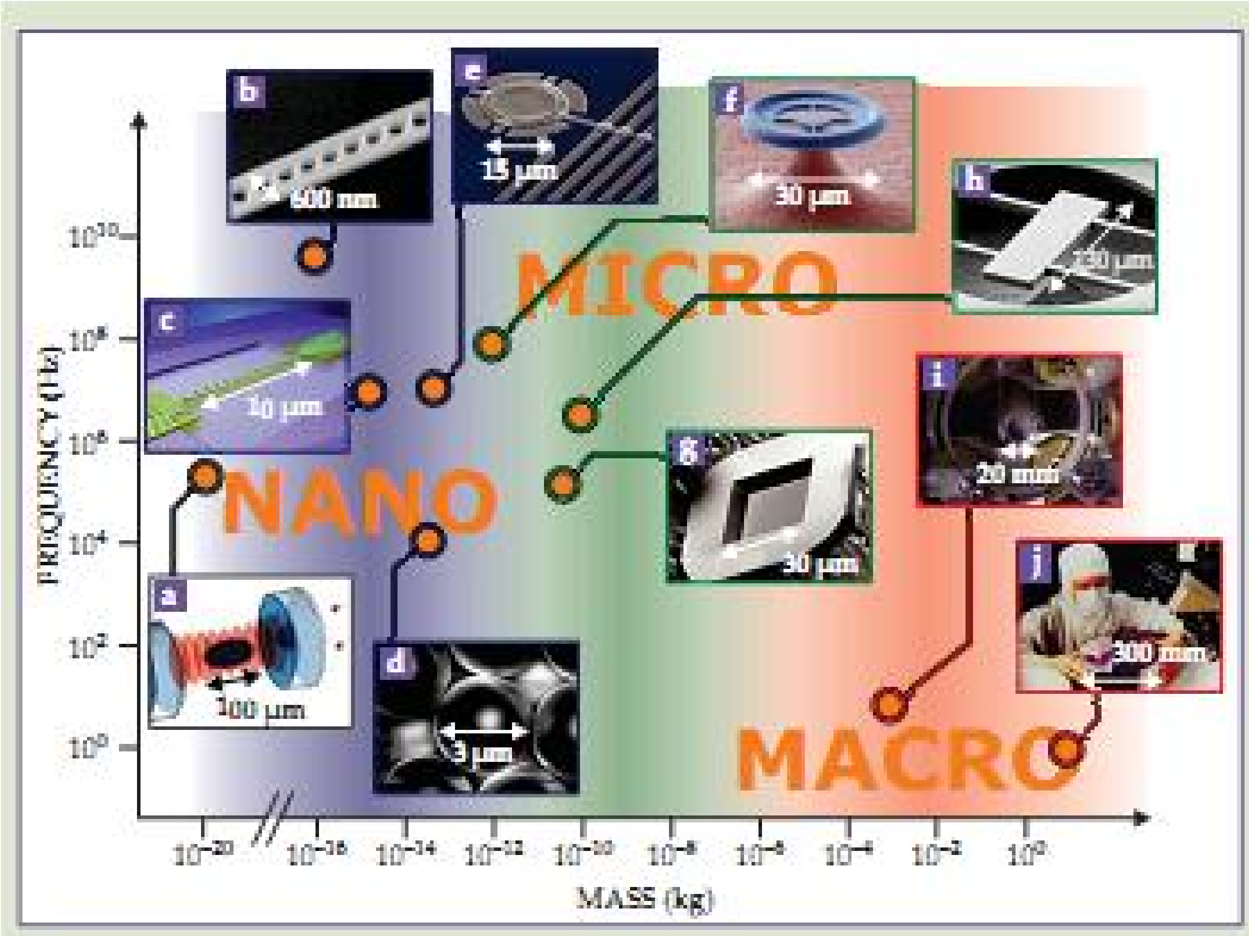
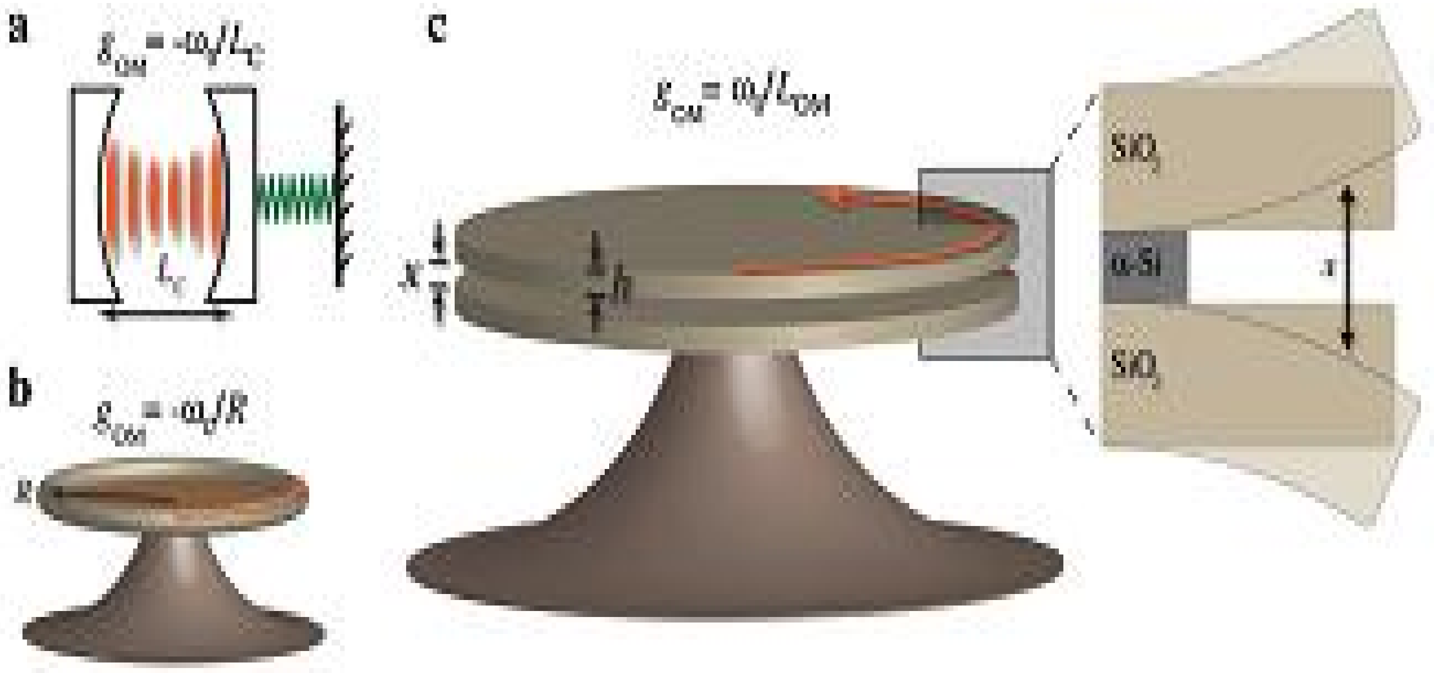
Konuşma İçeriği

- Motivasyon ve nano-mekanik aletlerin örnekleri
- Işık basıncının tanımı
- Model Sistem A : Tek taraflı nano-mekanik kovuklu sistem
- Model Sistem B : Çift taraflı nano-mekanik kovuklu sistem
- Sonuçlar ve Tartışmalar

Motivasyon ve Deneysel Örnekler



Physics Today, (July **2012) 29**



PRL, 103, 103601 (2009)

Motivasyon ve Deneysel Örnekler

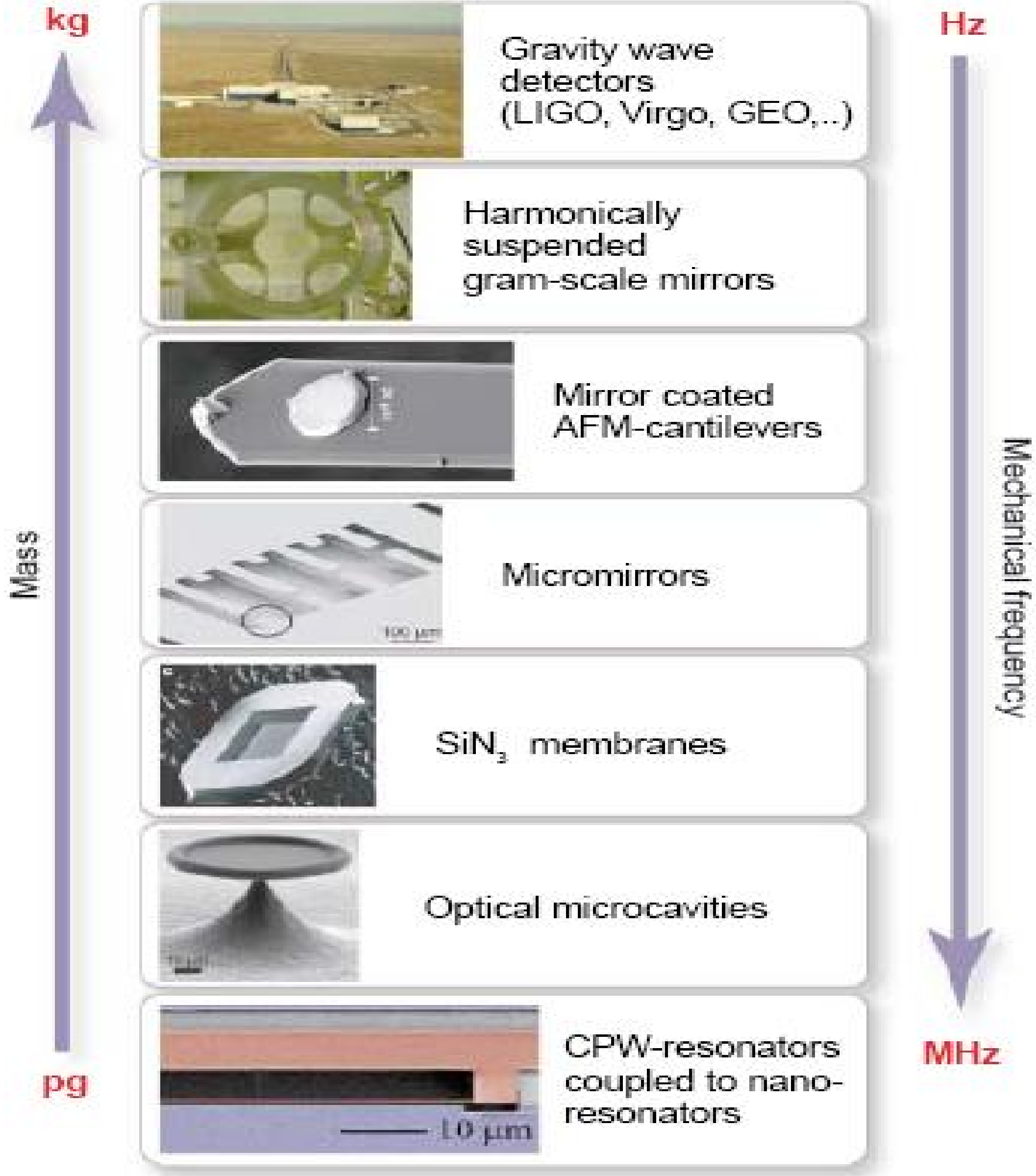
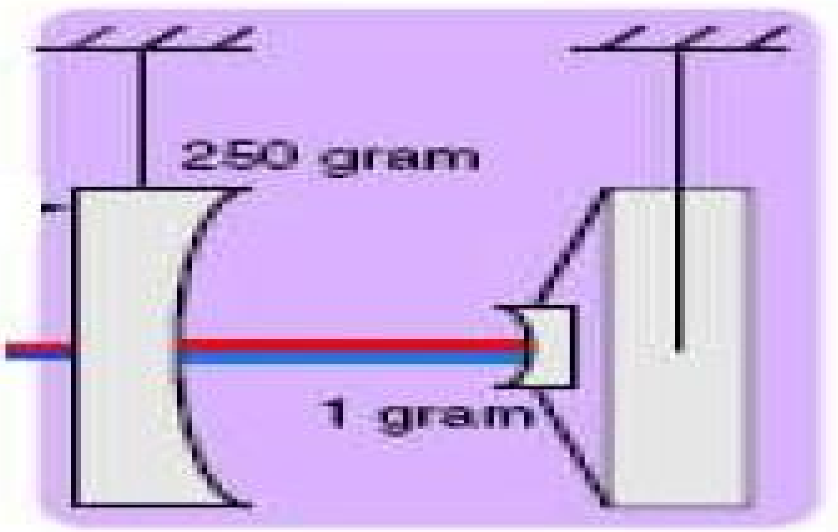


Fig. 3. Experimental cavity optomechanical systems. (**Top** to **Bottom**) Gravitational wave detectors [photo credit LIGO Laboratory], harmonically suspended gram-scale mirrors (*28*), coated atomic force microscopy cantilevers (*29*), coated micromirrors (*14*, *15*), SiN_3 membranes dispersively coupled to an optical cavity (*31*), optical microcavities (*13*, *16*), and superconducting microwave resonators coupled to a nanomechanical beam (*33*). The masses range from kilograms to picograms, whereas frequencies range from tens of megahertz down to the hertz level. CPW, coplanar waveguide.

T. Kippenberg and K. Vahala, Science 321, 1172 (2008).

Harmonik olarak tutturulmuş gram-skalasında ayna



The 1 g end mirror is suspended by two optical fibers 300 μm in diameter, giving a natural frequency $\Omega_{\mathrm{m}} = 2\pi \times 172\mathrm{Hz}$ for its mechanical mode, with quality factor $\mathrm{Q}_{\mathrm{m}} = 3200$.

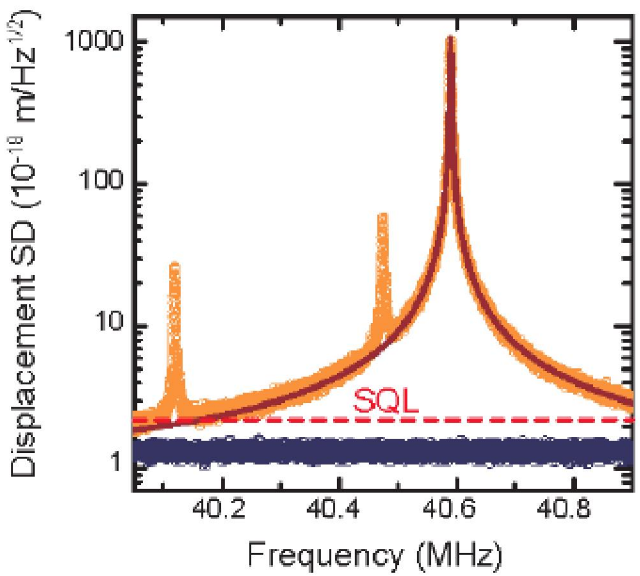
Phys. Rev. Lett. **98**, 150802 (2007).

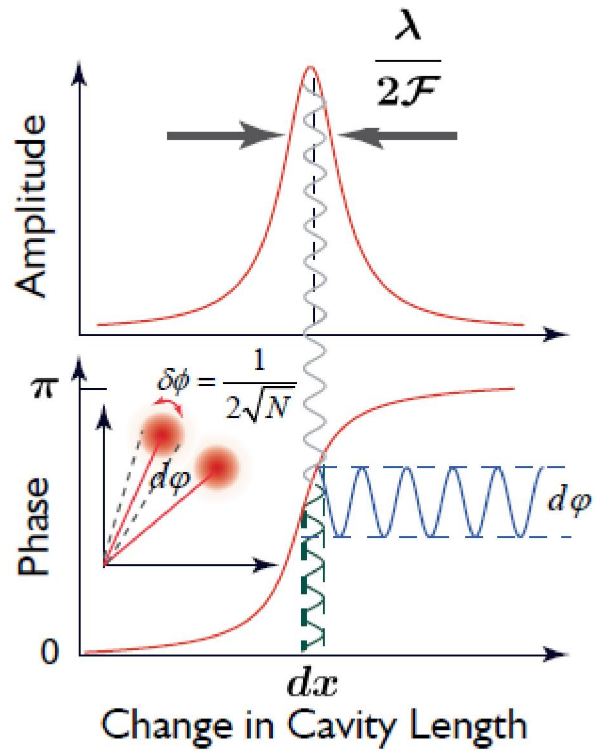
nature nanotechnology

LETTERS

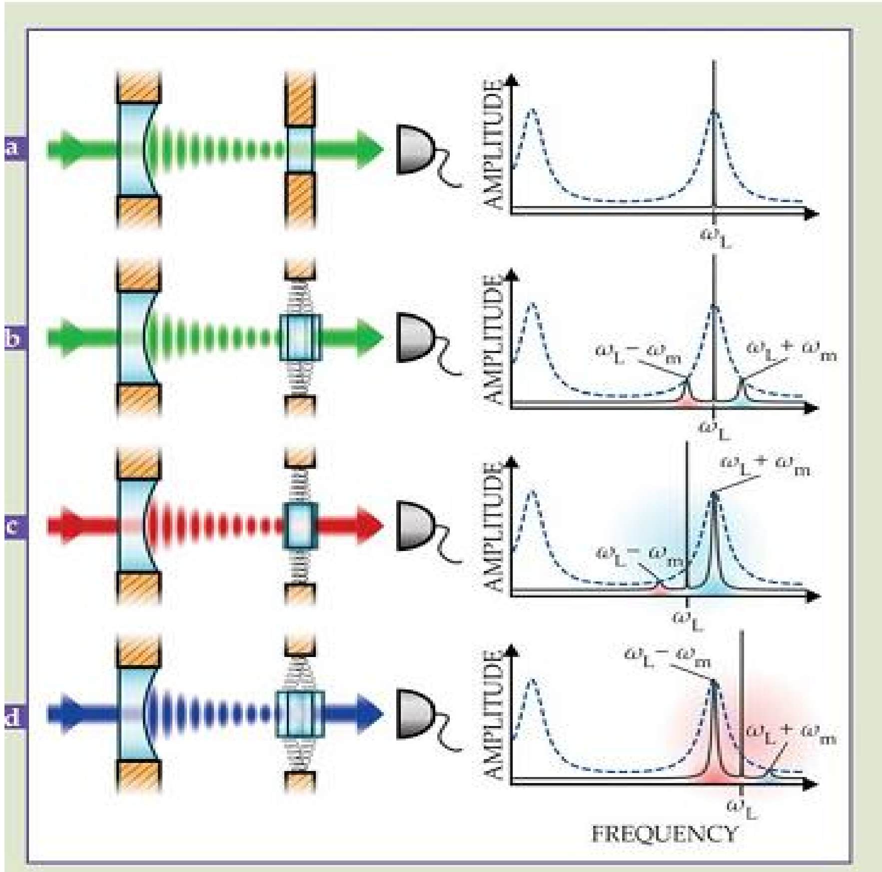
PUBLISHED ONLINE: 24 JUNE 2012 | DOI: 10.1038/NNANO.2012.97

A hybrid on-chip optomechanical transducer for ultrasensitive force measurements



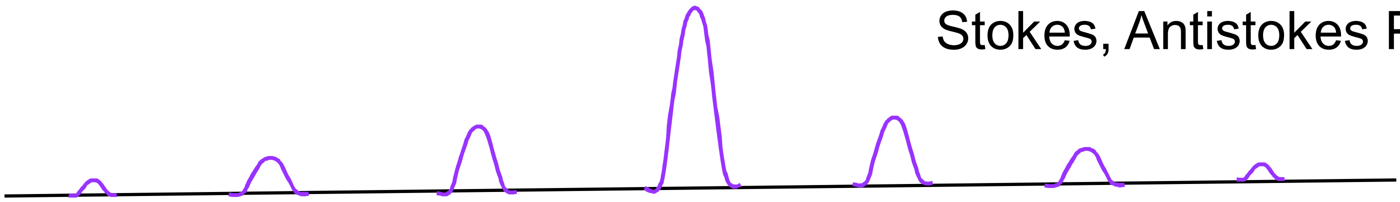


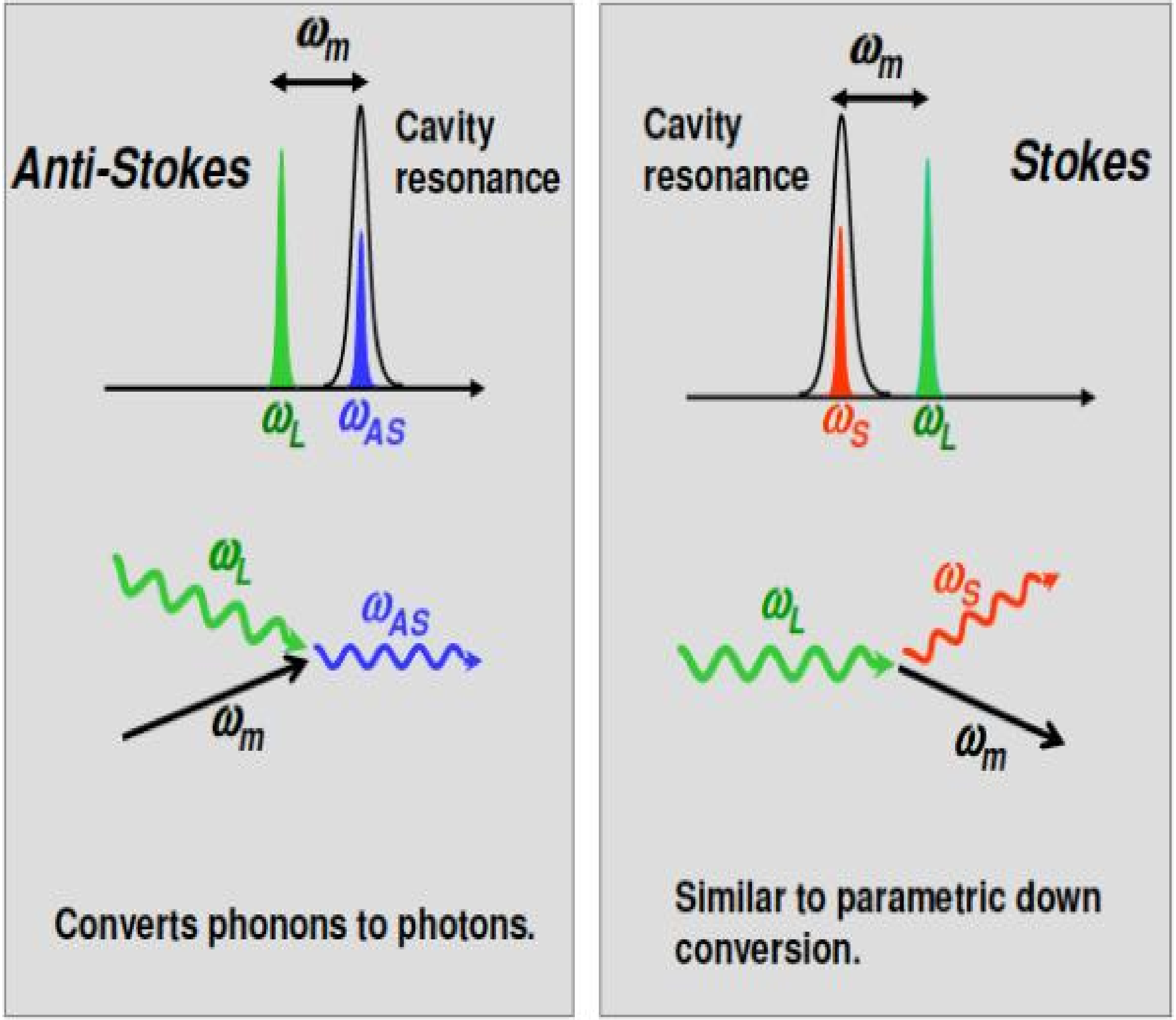
Soğutma İşlemi



Physics Today, July 2012

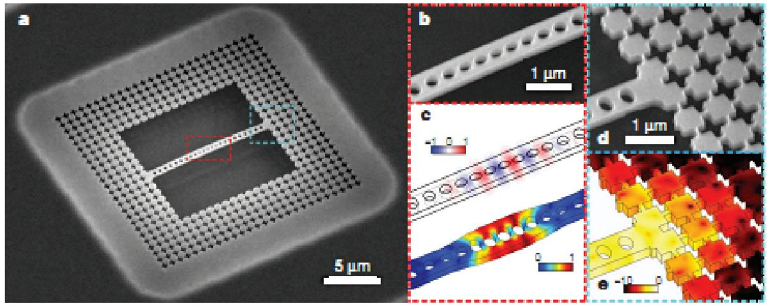
Stokes, Antistokes Processes

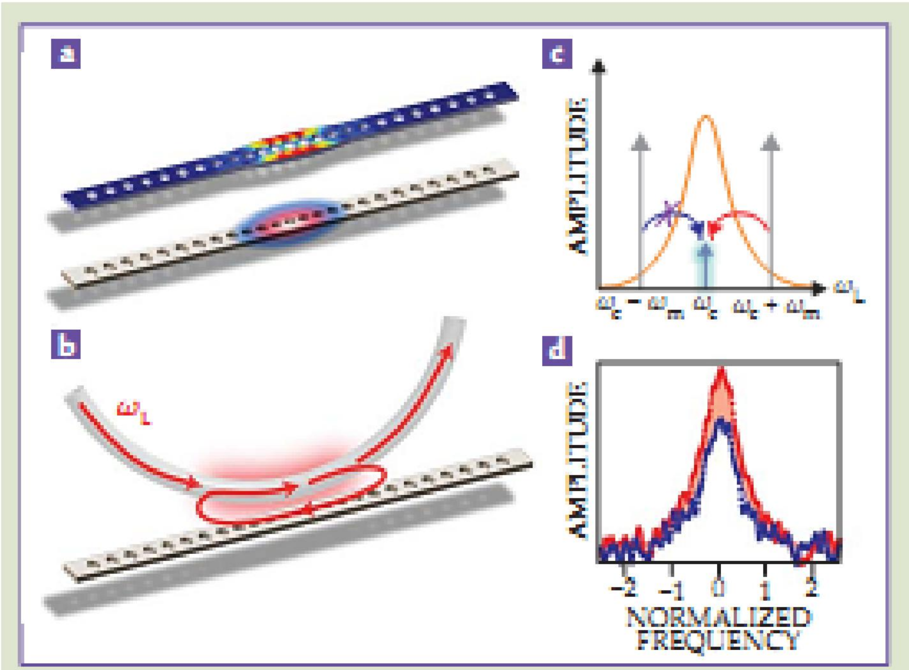




Red detuned driving **Blue detuned driving**

Laser cooling of a nanomechanical oscillator into its quantum ground state





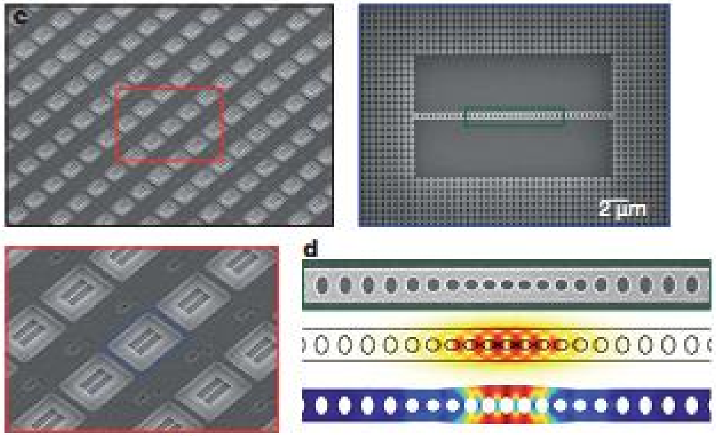
$$\langle x^2 \rangle = \frac{\hbar}{m\omega_m}\left(0.5 + \frac{1}{e^{\hbar\omega_m/(k_B T)} - 1}\right)$$

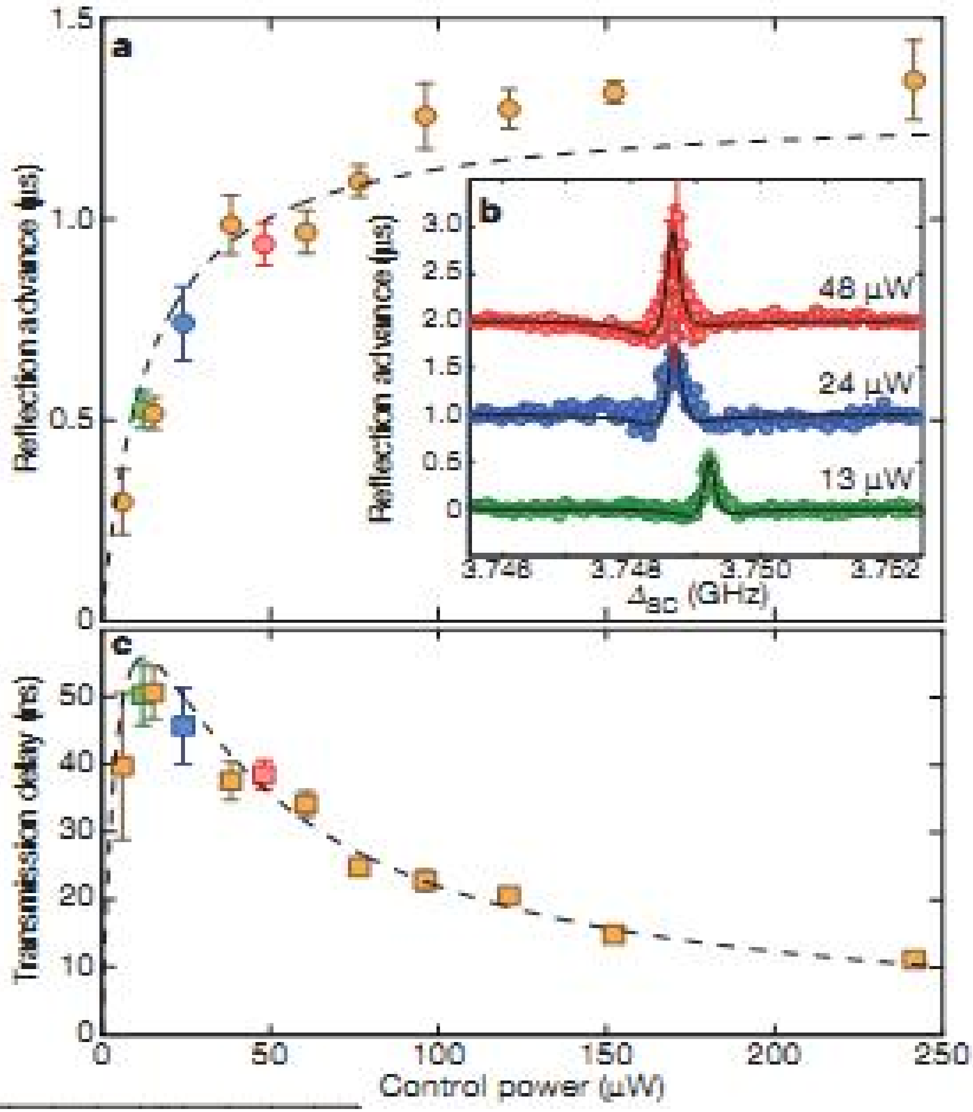
For $\omega_m = 2\pi \times 947 \times 10^3$ Hz, $T = 41.4\mu$K,

$$\frac{1}{e^{\hbar\omega_m/(k_B T)} - 1} = 0.5.$$

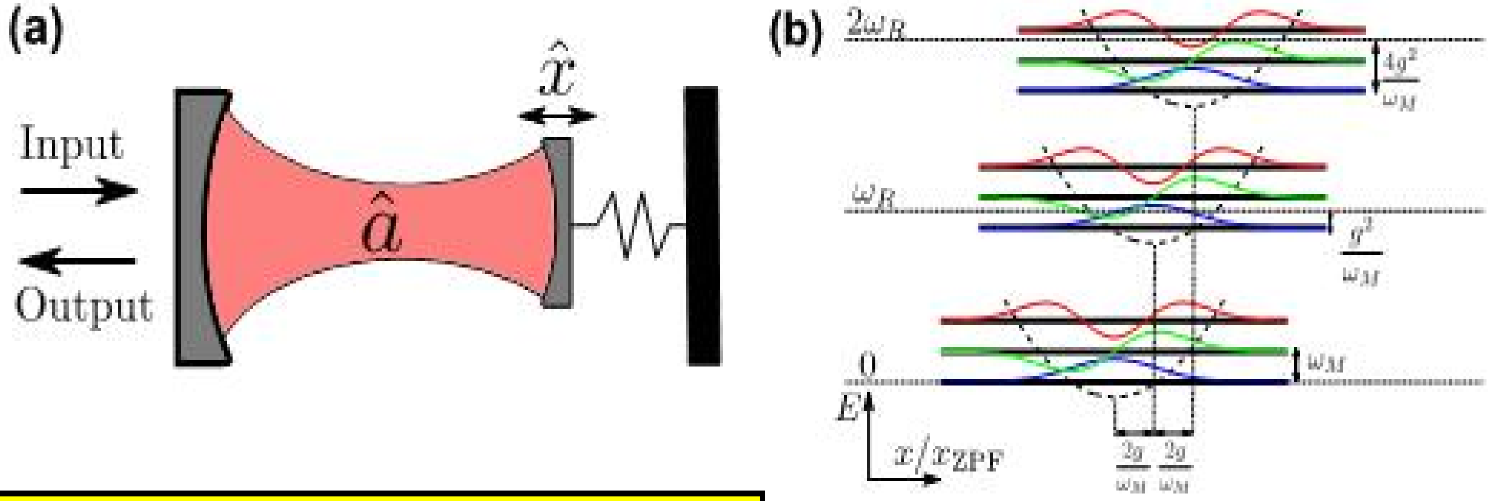
Nature 478, 89 (2011)

Electromagnetically induced transparency and slow light with optomechanics

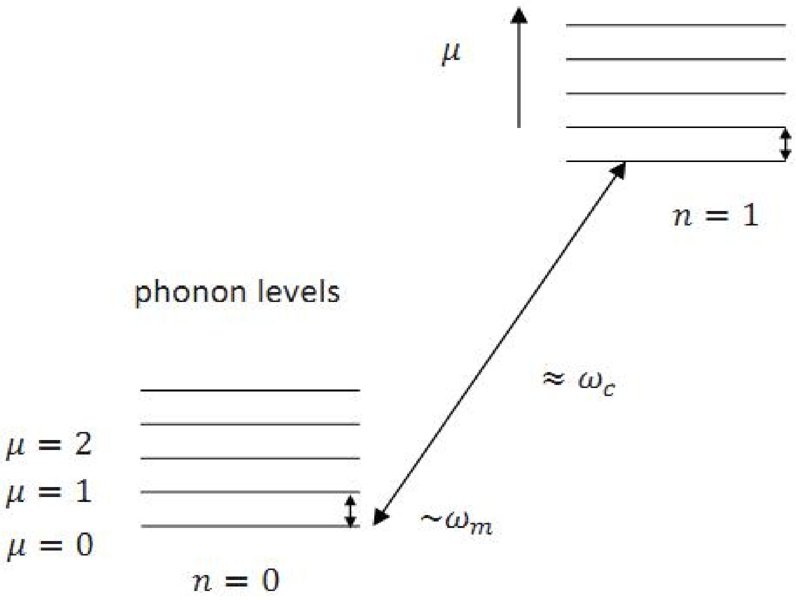




Nature 472, 69 (2011)



$$H_0 = \hbar\omega_0 a^+ a + \hbar\omega_m b^+ b + Gga^+ a(b + b^+)$$

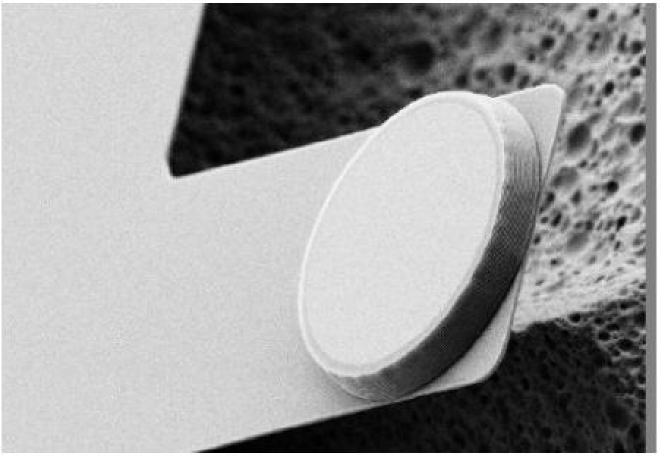


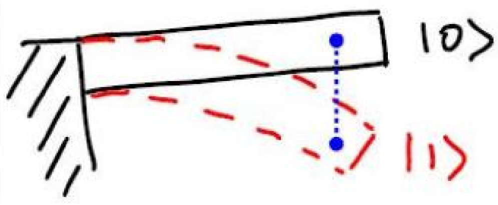
$$|\Psi_\mu^{(n)}\rangle = \mathcal{D}^\dagger\left(\frac{Gn}{\omega_m}\right)|n, \mu\rangle,$$

$$\mathcal{E}_\mu^{(n)} = n\hbar\omega_c + \mu\hbar\omega_m - \hbar\frac{G^2 n^2}{\omega_m}.$$

PRL, 107, 063602 (2011)

Makroskopik kuantum fenomolojisini gösterimde ne kadar ileri gidebiliriz?





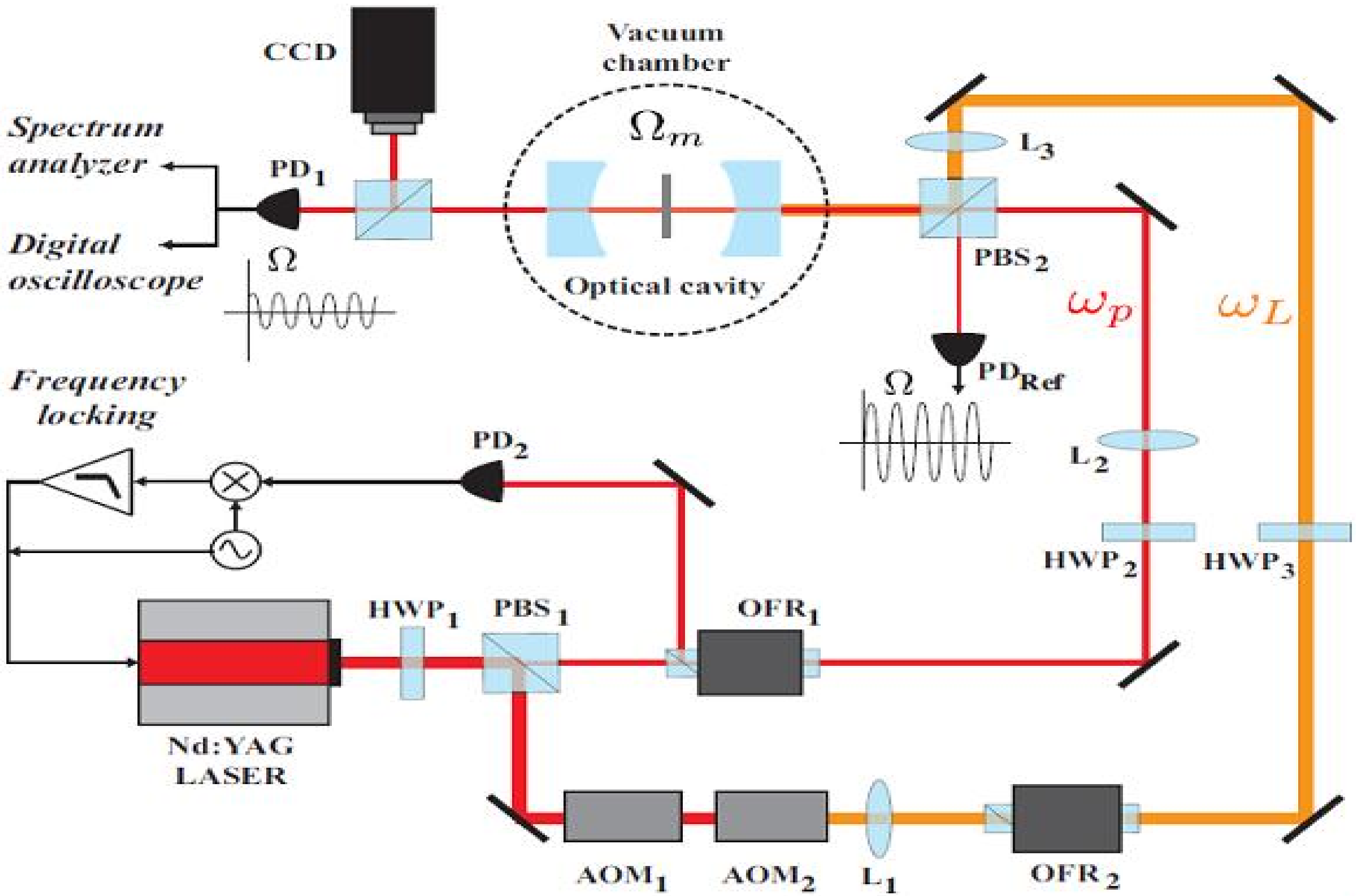
Superposition of macroscopically distinct states?

Optical detection of **Schrodinger cat states of a cantilever**

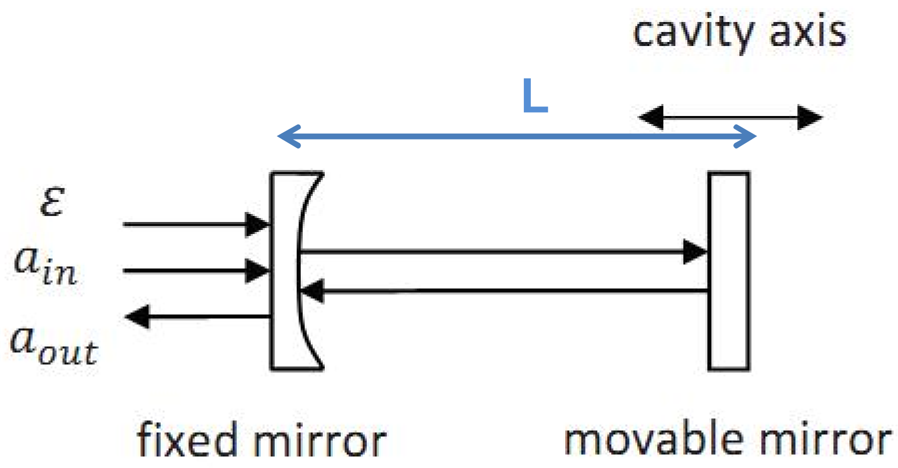
"membrane in the middle"

Fabry-Perot cavity with a thin SiN membrane inside
(J. Kimble Caltech)
Harris-Yale,
D. Vitali-University of Camerino Italy

Ortasında zar olan Çift taraflı nano-mekanik kovuklu sistemde Optomekaniksel indirgenmiş Saydamlık Deneyi



Karuza et al., PRA 88, 013804 (2013)



$$H = \hbar\omega_0 c^+ c + g c^+ c x + \frac{p^2}{2m} + \frac{1}{2} m\omega_m^2 q^2 + i\hbar\varepsilon(c^+ e^{-i\omega_c t} - c e^{i\omega_c t})$$

1 2 3 4

Birinci terim kovuk alanın enerjisi

İkinci terim hareket edebilen aynayla kavite alanı arasındaki etkileşmeyi belirten optomekaniksel sabit parametre.

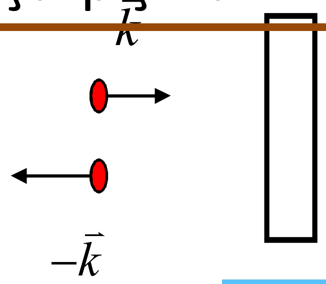
Üçüncü terim hareket edebilen aynanın enerjisi.

Dördüncü terim laser gücünün temsil ettiği enerji

$$\varepsilon = \sqrt{2\kappa\wp/(\hbar\omega_l)}.$$

Işık basıncının tanımı:

Elastik çarpışma



$$\Delta p = p_f - p_i = -\hbar k - \hbar k = -2\hbar k$$

Kovuk içinde yolculuk zamanı $t = 2L/c$,

n_0 ayna üzerine vuran toplam foton sayıay:

$$\Delta p_{total} = n_0 \Delta p = -2n_0 \hbar k$$

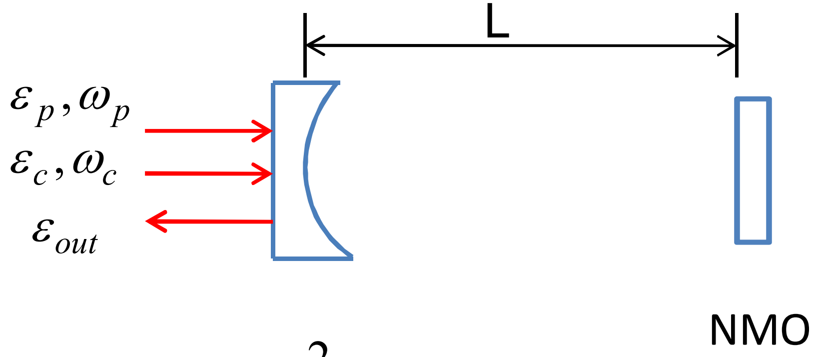
impulse-momentum teoremi

$$\Delta p_{total} = Ft$$

Işık basınç kuvveti:

$$F_{rad} = -F = -\frac{\Delta p_{total}}{t} = \frac{2n_0\hbar k}{2L/c} = \frac{n_0\hbar k}{L/c} = \frac{n_0\hbar\omega_0/c}{L/c} = \frac{n_0\hbar\omega_0}{L}$$

Model Sistem A : Tek taraflı nano-mekanik kovuklu sistem



$$H_{\text{int}} = -Fq = -\frac{\hbar\omega_0}{L} c^+ c\, q$$

$$H = \hbar\omega_0 c^+ c + \frac{p^2}{2m} + \frac{1}{2} m\omega_m^2 q^2 + i\hbar\varepsilon_c (c^+ e^{-i\omega_c t} - c e^{i\omega_c t})$$

cavity field — NMO — pump field-cavity field

$$+ i\hbar (c^+ \varepsilon_p e^{-i\omega_p t} - c\varepsilon_p^* e^{i\omega_p t}) - \chi_0 c^+ c q$$

probe field-cavity field — cavity field-NMO

where $\chi_0 = \hbar\omega_0 / L$ --- optomechanical coupling constant,

$$\varepsilon_c = \sqrt{2\kappa P_c / (\hbar\omega_c)}, \varepsilon_p = \sqrt{2\kappa P_{pr} / (\hbar\omega_p)}.$$

Model Sistem A

$$\varepsilon_{out}(t) = \varepsilon_{out0} + \varepsilon_{out+}e^{-i\delta t} + \varepsilon_{out-}e^{i\delta t}$$

$$\varepsilon_{out}(t) + \varepsilon_p e^{-i\omega_p t} + \varepsilon_c e^{-i\omega_c t} = 2\kappa\langle\tilde{c}\rangle$$

$$\varepsilon_T = 2\kappa\tilde{c}_+ = \frac{2\kappa}{d(\delta)}\{(\delta^2 - \omega_m^2 + i\gamma_m\delta)[\kappa - i(\Delta+\delta)] - 2i\omega_m\beta\},$$

where

$$d(\delta) = [\delta^2 - \omega_m^2 + i\gamma_m\delta][(\kappa - i\delta)^2 + \Delta^2] + 4\Delta\omega_m\beta,$$

$$\delta = \omega_p - \omega_c, \quad \Delta = \omega_0 - \omega_c - \frac{2\beta\chi_0}{\omega_m}, \quad \beta = \frac{\chi_0^2|\tilde{c}_0|^2}{2m\hbar\omega_m}, \quad \tilde{c}_0 = \frac{\varepsilon_c}{\kappa + i\Delta}.$$

Radiation pressure modified detuning

Coupling field dependent

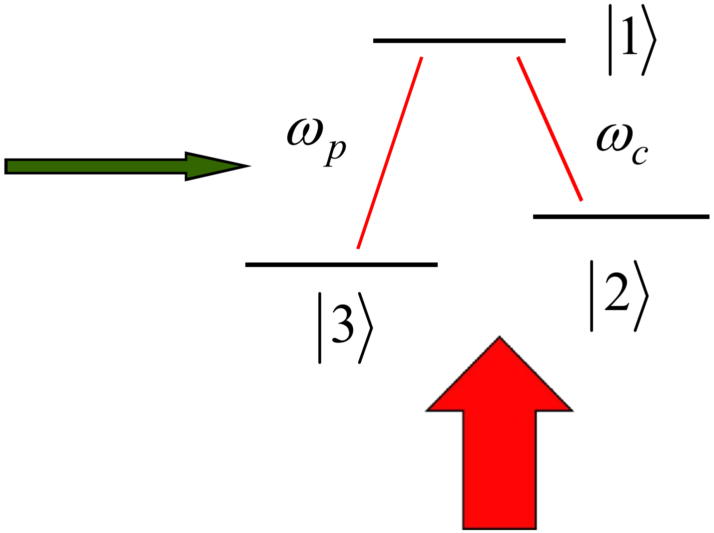
Fiziksel yaklaşım:

- Sideband resolved limit $\omega_m >> \kappa$
- $\kappa >> \gamma_m$

Condition for EIT in a optomechanical system

$$\varepsilon_T = \nu_p + i\tilde{\nu}_p = \frac{2\kappa}{\kappa - ix + \cfrac{\beta}{\cfrac{\gamma_m}{2} - ix}};$$

$$\text{where} \quad x = \delta - \omega_m.$$



PRA 81,041803(R) (2010)

Deneysel Parameterler

Seçilen parametreler:

$$\lambda = \frac{2\pi c}{\omega_c} = 1064\text{nm} \qquad L = 25\text{mm} \qquad m = 145\text{ng}$$

$$\kappa = 2\pi \times 215 \times 10^3\,\text{Hz} \qquad \omega_m = 2\pi \times 947 \times 10^3\,\text{Hz}$$

$$\kappa / \omega_m = 0.227$$

$$Q = \frac{\omega_m}{\gamma_m} = 6700$$

The ground state cooling condition $\kappa << \omega_m$

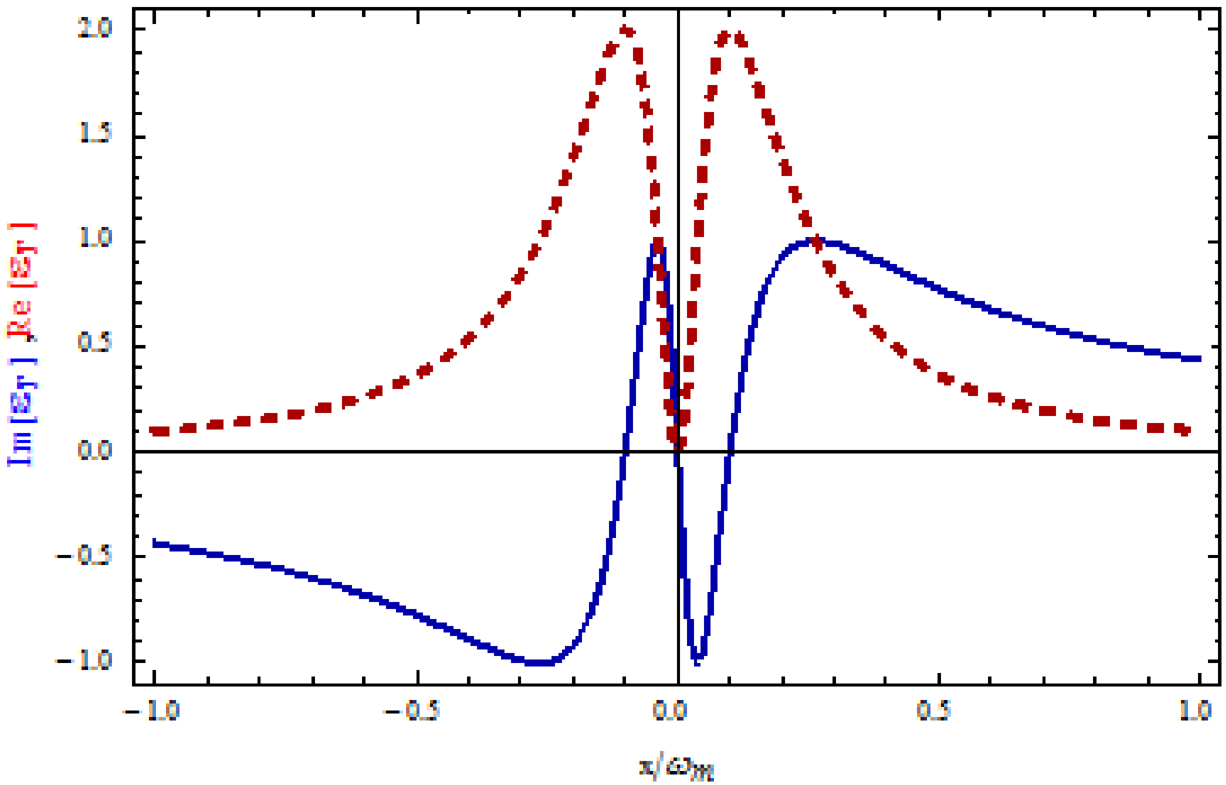
→ $P_c = 3.8\text{mW}$

I.Wilson-Rae et al., Phys.Rev.Lett.**99**,093901(2007);
F.Marquardt et al., Phys.Rev.Lett.**99**,093902(2007);
A.Schliesser et al., Nature Physics **4**,415(2008).

S. Gröblacher, K. Hammerer, M. R. Vanner, M. Aspelmeyer, Nature, **460**, 724 (2009).

Real ve imajiner kısım

$P_c = 3\text{mW}$

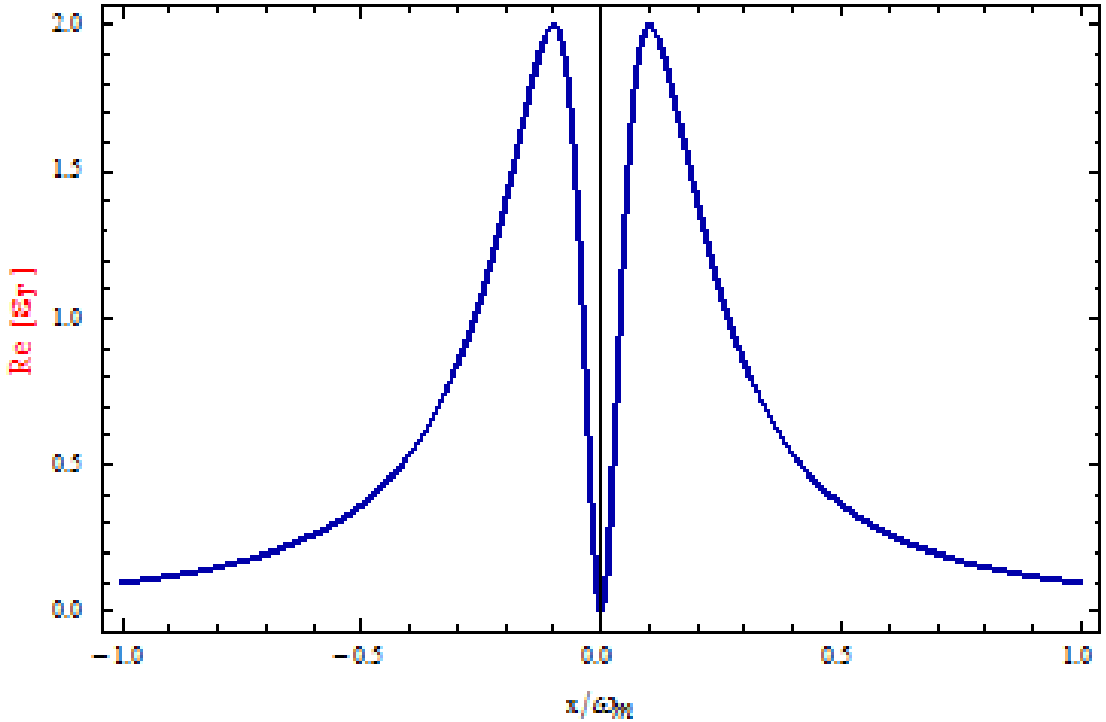


$$\varepsilon_T = 2\kappa \tilde{c}_+ = \frac{2\kappa}{d(\delta)}\{(\delta^2 - \omega_m^2 + i\gamma_m \delta)[\kappa - i(\Delta + \delta)] - 2i\omega_m \beta\},$$

Analog of EIT

G. Agarwal, S. Huang, PRA 81,041803(R) (2010)

Real Kısım $P_c = 3\text{mW}$



Analog of EIT

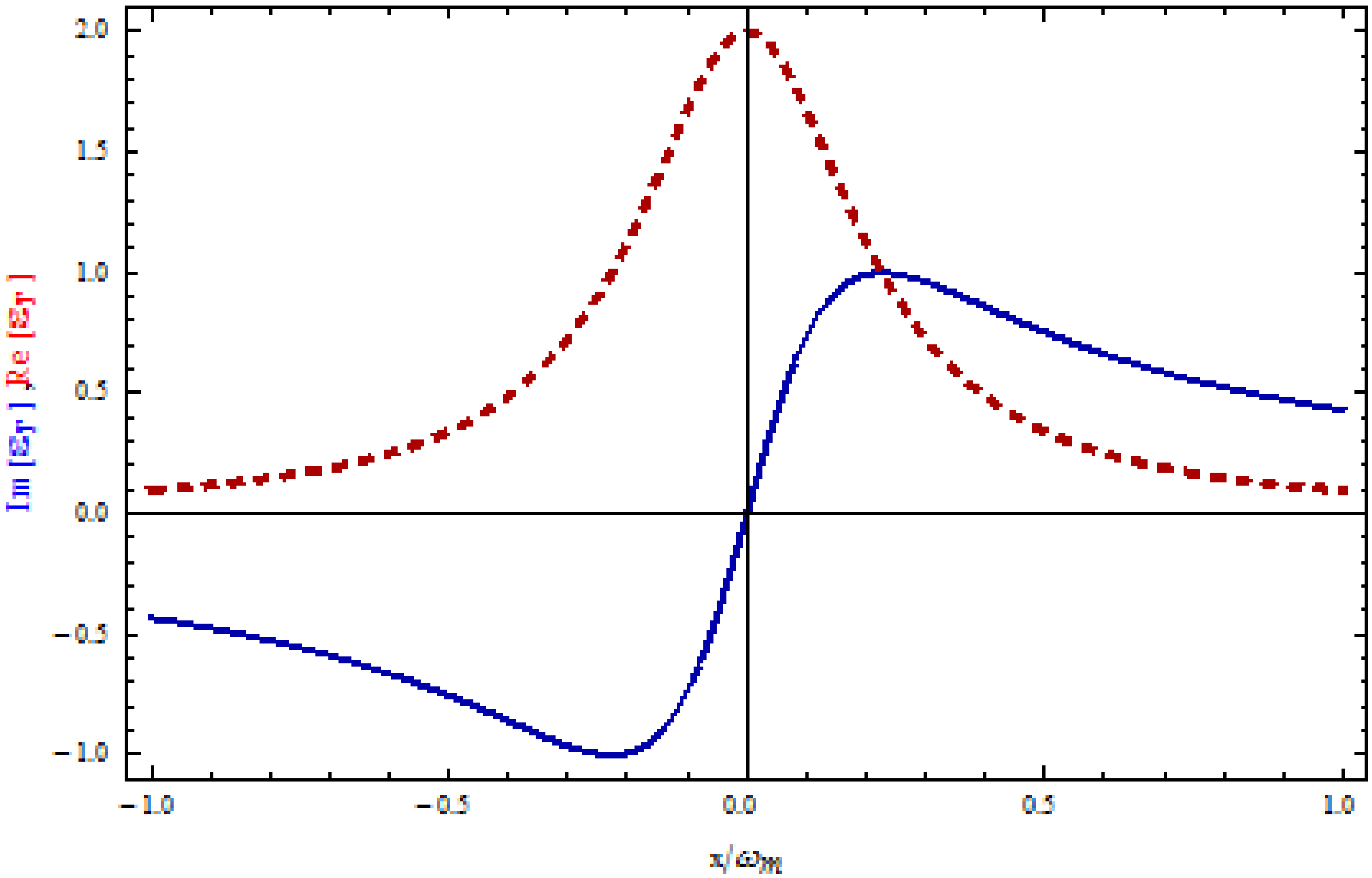
Power dependent

Width of the EIT hole:

$$\frac{\gamma_m}{2} + \frac{\beta}{\kappa}$$

G. Agarwal, S. Huang, PRA 81,041803(R) (2010)

Real ve imajiner kısım



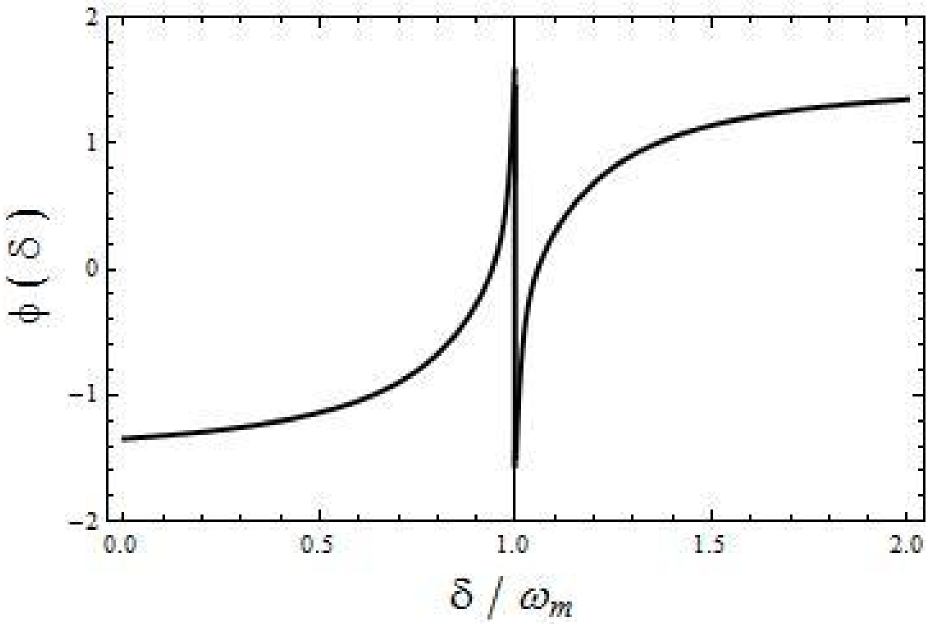
$$P_c = 0$$

Analog of EIT

PRA 81,041803(R) (2010)

Model A'daki sonuçlar

$$\varepsilon_{out+} = |T| e^{i\phi(\omega_p)}$$

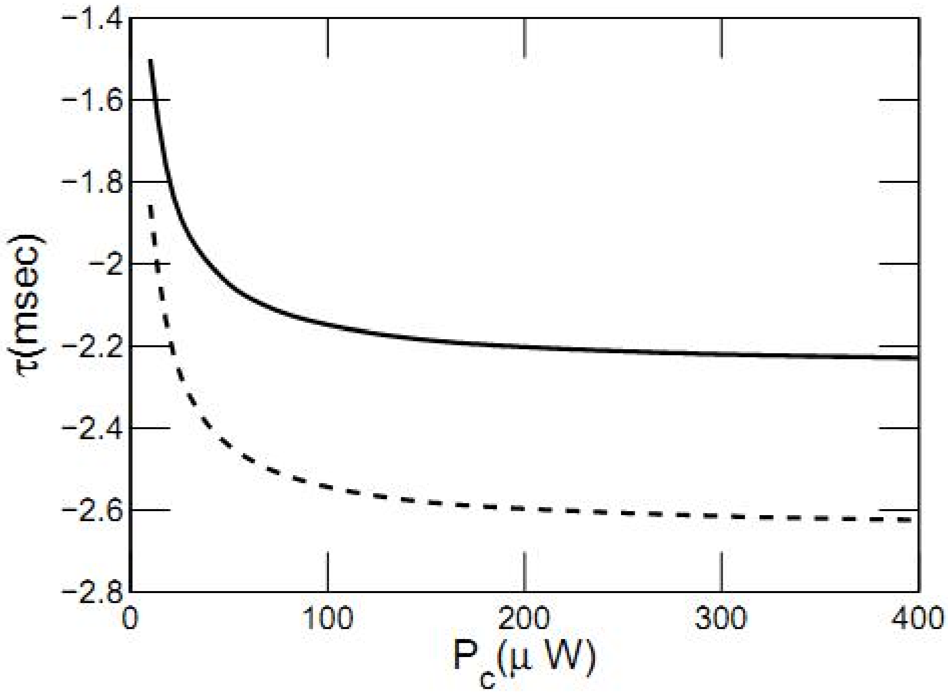


$$\phi(\omega_p) = \phi(\bar{\omega}) + (\omega_p - \bar{\omega}) \frac{\partial \phi}{\partial \omega_p}\bigg|_{\bar{\omega}}$$

$$\phi = \frac{1}{2i} \ln\left(\frac{E_T}{E_T^{\ *}}\right)$$

FIG. 3: Phase as a function of normalized frequency δ/ω_m for input coupling laser power $P_c = 1$ mW. The parameters are the same as Fig. (2).

Model A'daki sonuçlar



$$\tau = \left.\frac{\partial \phi}{\partial \omega_p}\right|_{\omega}$$

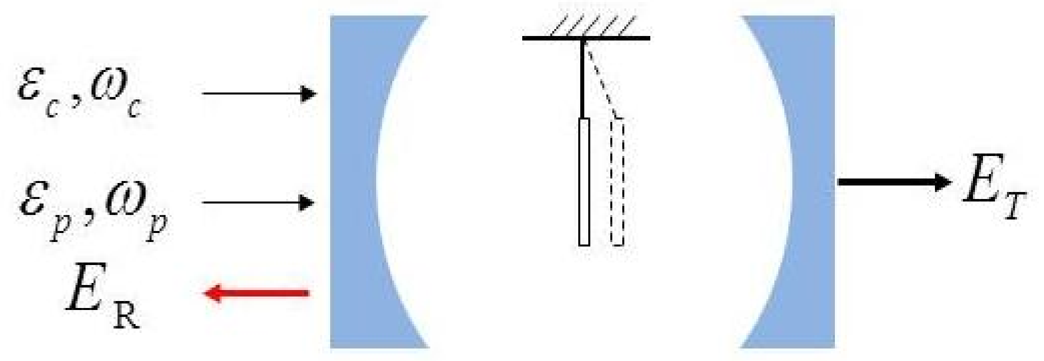
Group delay as a function of the pump power. Time delay of the probe in the presence of the coupling field as a function of the power of the pumping or coupling field

Acta Physica Polonica A 124, 46-49 (2013).

$$\gamma_m = 2\pi \times 141\text{Hz} \ \ \text{(solid line)}$$

$$\gamma_m = 2\pi \times 120\text{Hz} \ \ \text{(dashed line)}$$

Model Sistem B: Çift taraflı nano-mekanik kovuklu sistem



$$H = \hbar(\omega_0 - \omega_0)c^+c + \frac{p^2}{2m} + \frac{1}{2}m\omega_m^2 q^2 + i\hbar\varepsilon_c(c^+ - c)$$
$$+ i\hbar(c^+\varepsilon_p e^{-i\delta t} - c\varepsilon_p{}^* e^{i\delta t})$$

Heisenberg Hareket Denklemi:

$$\langle \mathrm{c(t)} \rangle = \langle \tilde{c}(t) \rangle e^{-i\omega_c t}$$

$$\dot{q} = \frac{p}{m}$$

$$\dot{p} = -m\omega_m^{\;2} q - \hbar g_0 \tilde{c}^{+} \tilde{c} - \gamma_m p$$

$$\dot{\tilde{c}} = -[2\kappa + i(\omega_0 - \omega_c + g\,q)]\tilde{c} + \varepsilon_c + \varepsilon_p e^{-i(\omega_p - \omega_c)t}$$

Durağan durum çözümü:

$$p_0 = 0, \quad q_0 = -\frac{\hbar\, g \left|c_0\right|^2}{m\,\omega_m^{\;2}}, \quad \tilde{c}_0 = \frac{\varepsilon_c}{2\kappa + i\Delta},$$

burada $\Delta = \omega_0 - \omega_c + g\,q_0$

Model Sistem B

Zayıf alan sürücü alandan çok zayıf
Probe much weaker than coupling field

$$q(t) = q_0 + q_+ \varepsilon_p e^{-i\delta t} + q_- \varepsilon_p{}^* e^{i\delta t},$$

$$p(t) = p_0 + p_+ \varepsilon_p e^{-i\delta t} + p_- \varepsilon_p{}^* e^{i\delta t},$$

$$c(t) = c_0 + c_+ \varepsilon_p e^{-i\delta t} + c_- \varepsilon_p{}^* e^{i\delta t},$$

$$p_0 = 0, \quad q_0 = -\hbar g \left|c_0\right|^2 / m\omega_m{}^2, \quad c_0 = \frac{\varepsilon}{2\kappa + i\Delta},$$

$$\Delta = \omega_0 - \omega_c + g q_0$$

Model Sistem B

Probe much weaker than coupling field

$$c_+(\delta) = \frac{m\{(\delta^2 - \omega_m^2 + i\gamma_m\delta)[2\kappa - i(\Delta+\delta)] - i\alpha\}}{m[\delta^2 - \omega_m^2 + i\gamma_m\delta][(2\kappa - i\delta)^2 + \Delta^2] + 2\Delta\alpha,},$$

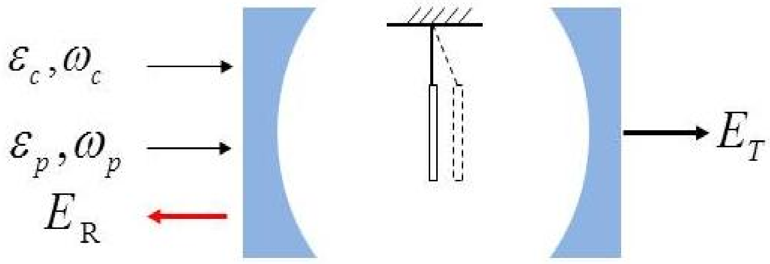
where

$$\delta = \omega_p - \omega_c, \quad \Delta = \omega_0 - \omega_c + g q_0,$$

$$\mathrm{q}_0 = -\frac{\hbar g\,|c_0|^2}{m\,\omega_m^2}, \quad c_0 = \frac{\varepsilon_c}{2\kappa + i\Delta}.$$

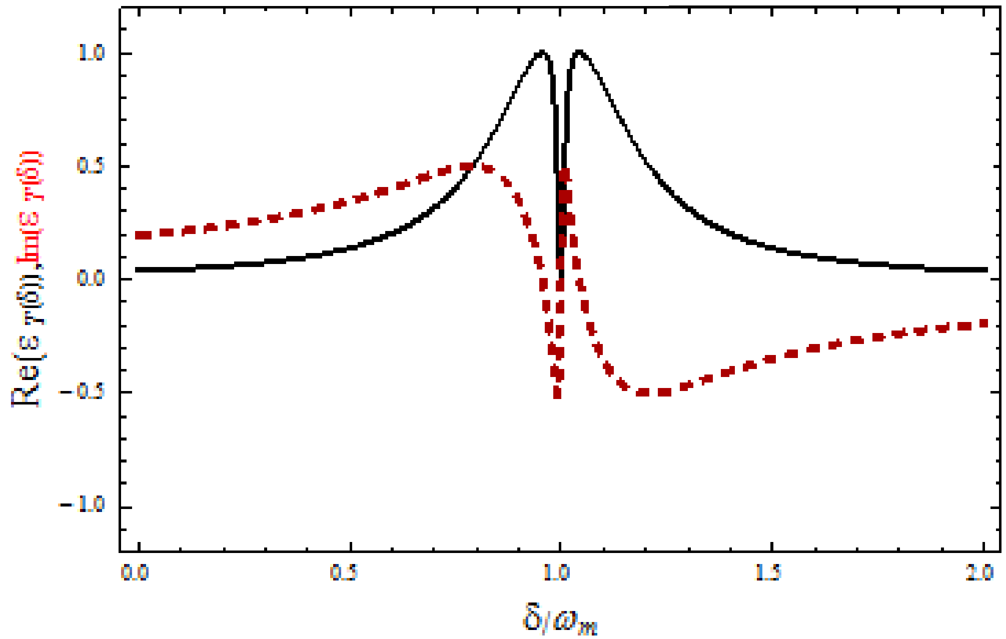
Sürücü alan bağımlı
Coupling field dependent

Sonuç ve Tartışmalar



$$E_R = (2\kappa c_+ - 1)\varepsilon_p e^{-i\omega_p t}$$

$$E_T = (2\kappa c_+)\varepsilon_p e^{-i\omega_p t}$$



Physical Review A **87**, 013824 (2013).

Sonuç ve Tartışmalar

EIT genişliği:

$$\Gamma = \frac{\gamma_m}{2} + \frac{\alpha(P_c)}{4 m \omega_m \kappa}, \quad \alpha(P_c) = \hbar g^2 |c_0|^2$$

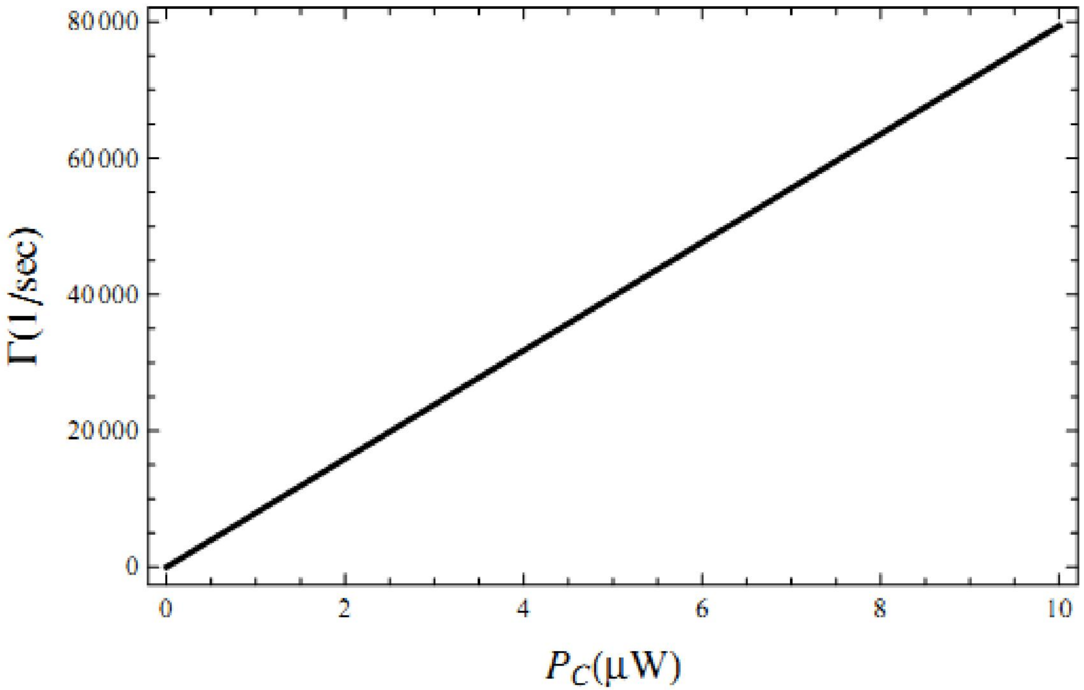
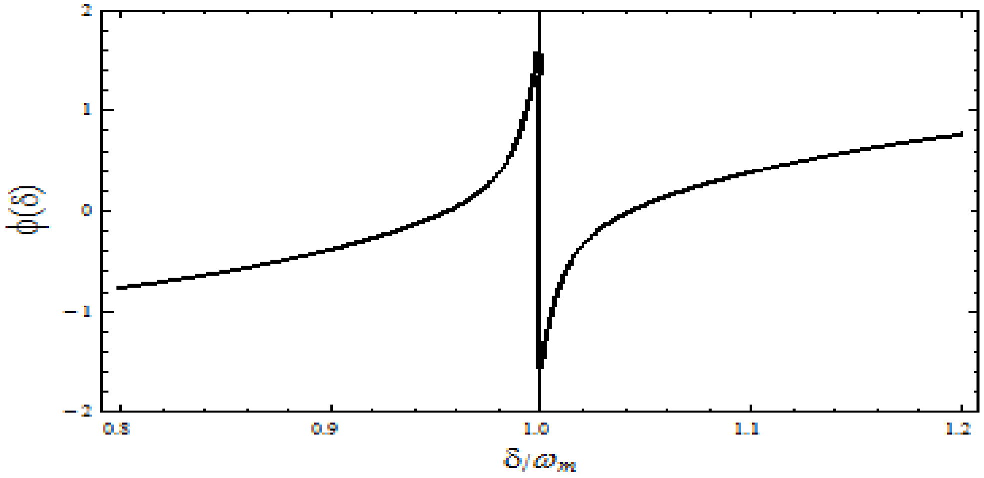


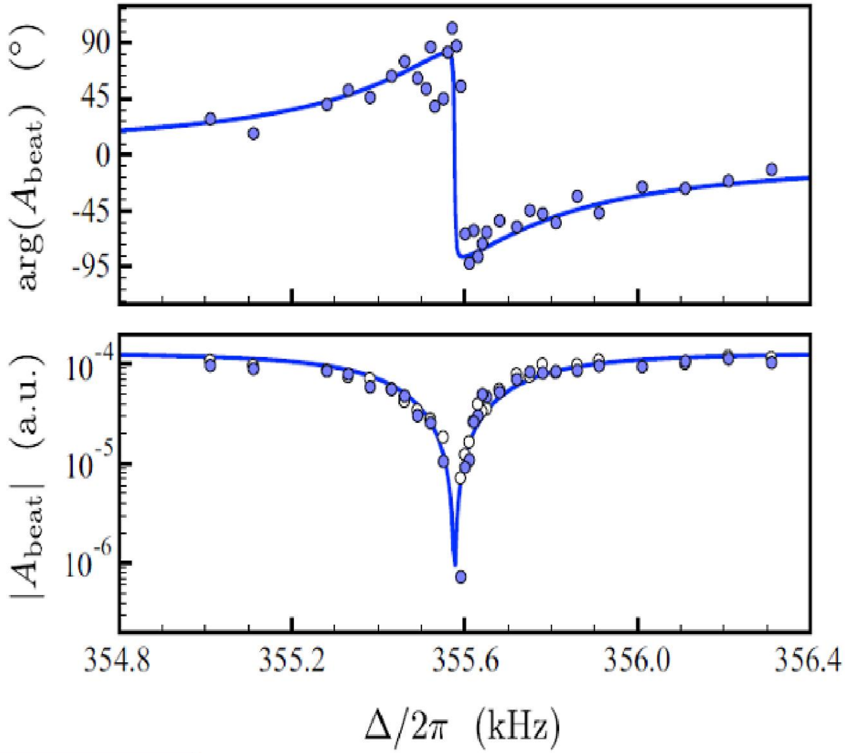
FIG. 8: The power dependent EIT width $\Gamma(\delta)$ as a function of normalized frequency with $\delta = \omega_m$. $P_c = 0$ solid, 5μW (dashed). All parameters are the same with those of Fig. 2.

Sonuç ve Tartışmalar

$$E_T = |T| e^{i\phi(\omega_p)}$$

$$\phi = \frac{1}{2i} \ln\left(\frac{E_T}{E_T^*}\right)$$

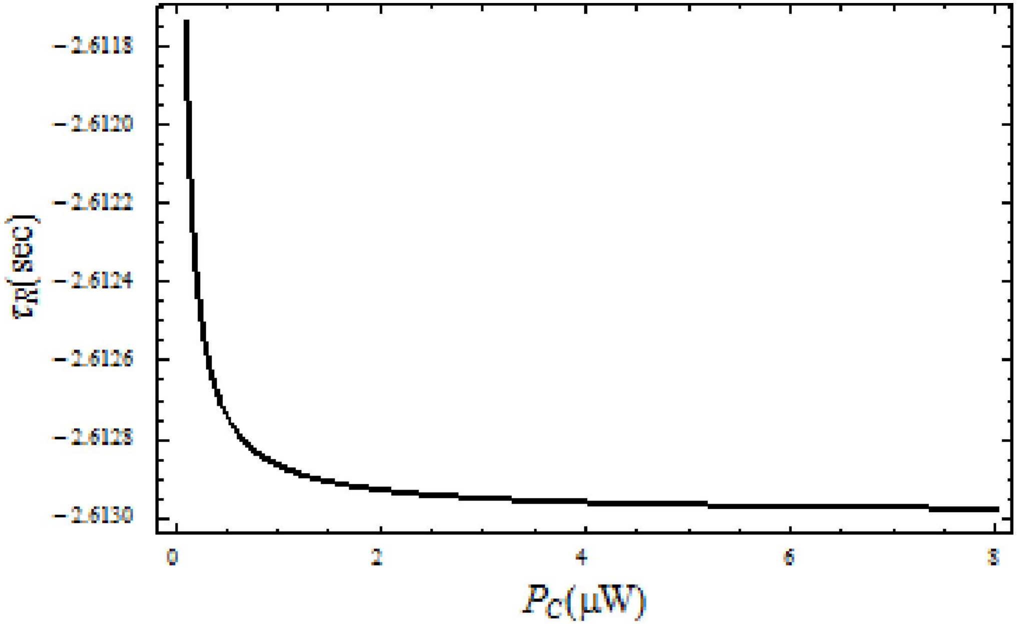




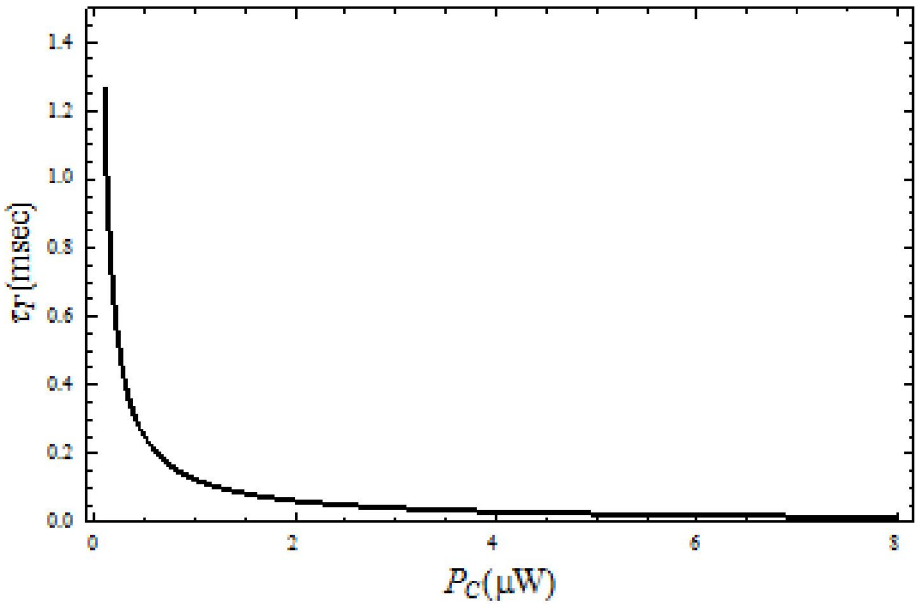
D. Tarhan et all.
Physical Review A **87**, 013824 (2013).

Karuza et al., PRA 88, 013804 (2013)

Sonuç ve Tartışmalar



$$\tau_R = \mathrm{Im}\{\frac{1}{\varepsilon_R}\frac{\partial \varepsilon_R}{\partial \omega_p}\}\bigg|_{\bar{\omega}}$$



$$\tau_T = \mathrm{Im}\{\frac{1}{\varepsilon_T}\frac{\partial \varepsilon_T}{\partial \omega_p}\}\bigg|_{\bar{\omega}}$$

Sonuç ve Tartışmalar

$$q(t) = q_0(t) + q_+(t)e^{-i\delta t} + q_-(t)e^{i\delta t},$$

$$p(t) = p_0(t) + p_+(t)e^{-i\delta t} + p_-(t)e^{i\delta t},$$

$$c(t) = c_0(t) + c_+(t)e^{-i\delta t} + c_-(t)e^{i\delta t},$$

Kuple olmuş normal mod uyarımları:

$$\frac{dq_+}{dt} = Aq_+ - Bc_+$$

$$\frac{dc_+}{dt} = Cc_+ - Dq_+ + \varepsilon_p(t)$$

Sonuç ve Tartışmalar

$$\vec{V} = \begin{pmatrix} q_+ \\ c_+ \end{pmatrix} \qquad \tilde{M} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \qquad \vec{F} = \begin{pmatrix} 0 \\ \varepsilon_p(t) \end{pmatrix}$$

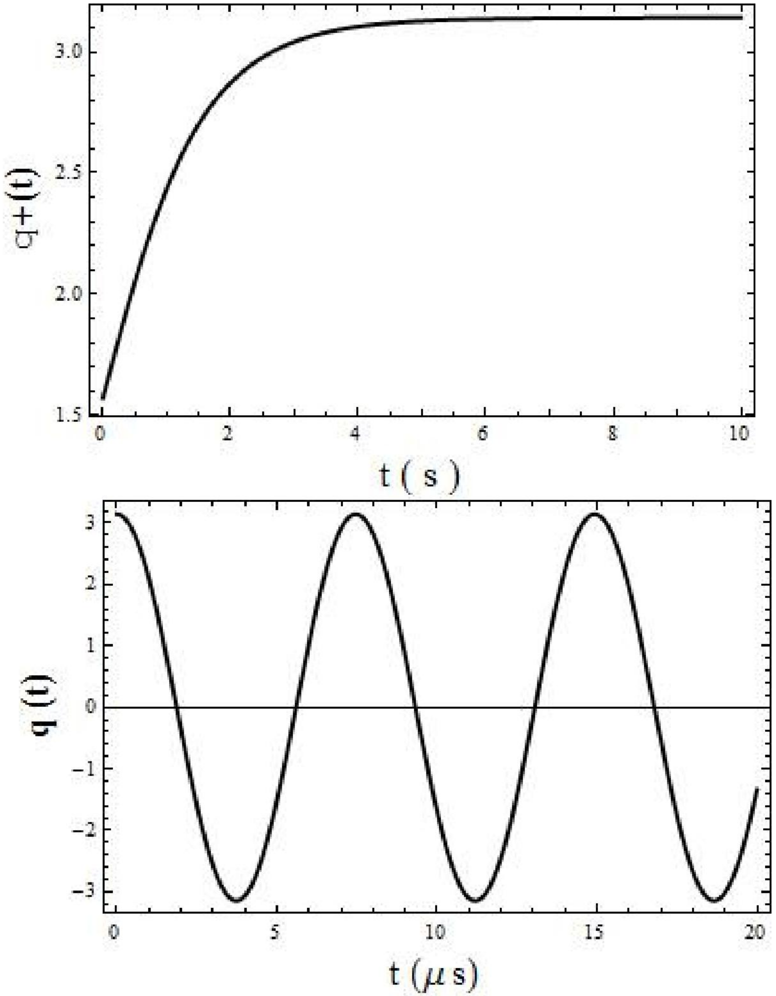
$$\frac{d}{dt}\vec{V} = -\tilde{M} \bullet \vec{V} + \vec{F} \quad \Rightarrow \quad \vec{V} = \tilde{M}^{-1}\,\vec{F}$$

$$\vec{V}(t) = e^{-\tilde{M}(t-t_0)}\vec{V}(t_0) + \int_{t_0}^{t} e^{-\tilde{M}(t-t')}\vec{F}(t')dt'$$

$$\vec{V}(t) = \int_{-\infty}^{t} e^{-\tilde{M}(t-t')}\vec{F}(t')dt'$$

Sonuç ve Tartışmalar

Zamana bağlı zayıf alan etkileşimli opto-mekanik sistemde ayna titreşimlerin kontrollü uyarımları



$$q(t) = q_0 + 2q_+(t)\cos(\delta t)$$

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Dinlediğiniz için Teşekkürler