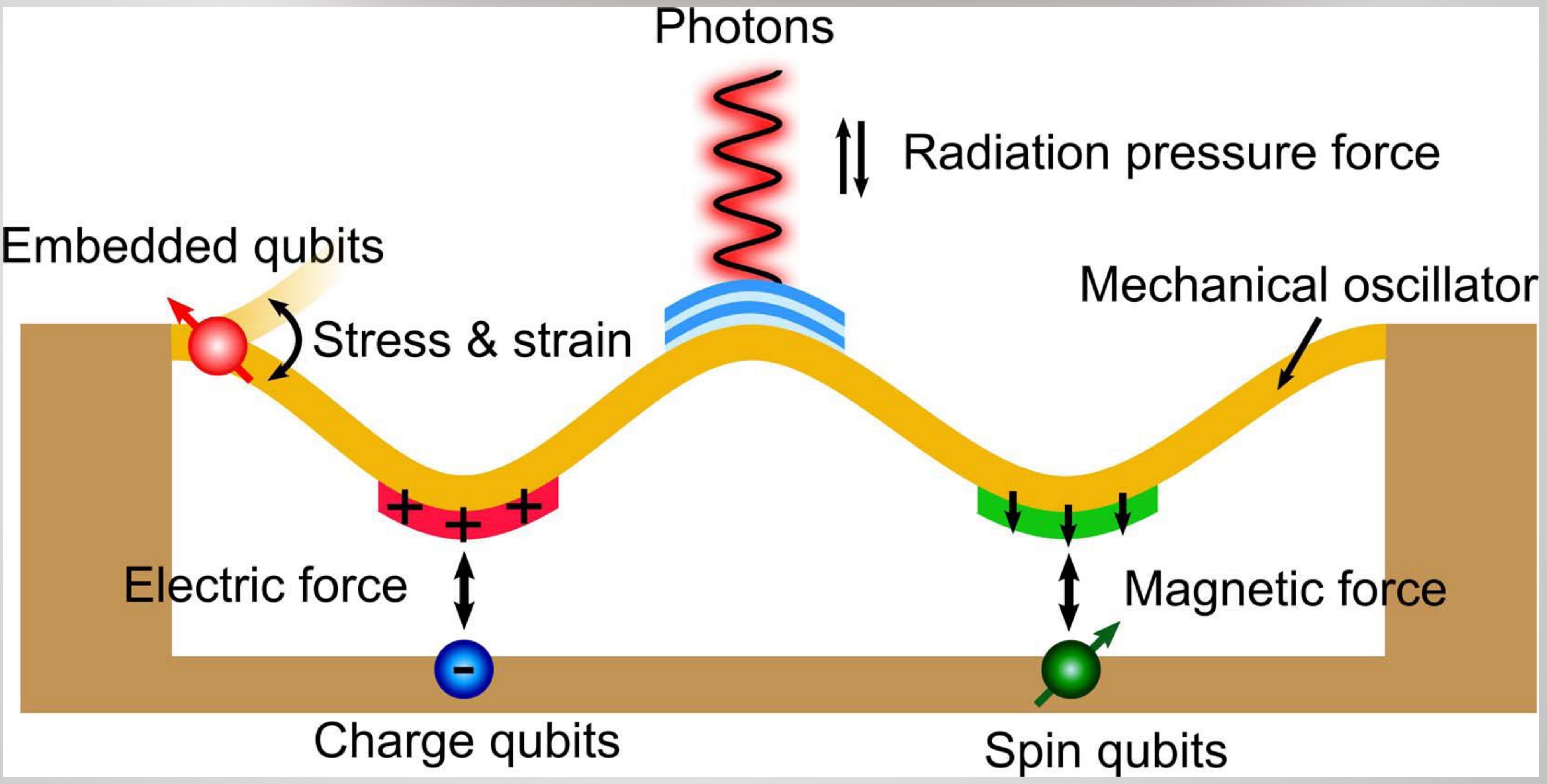
安徽理工大学

混合量子系统中光传输的量子调控

陈华俊

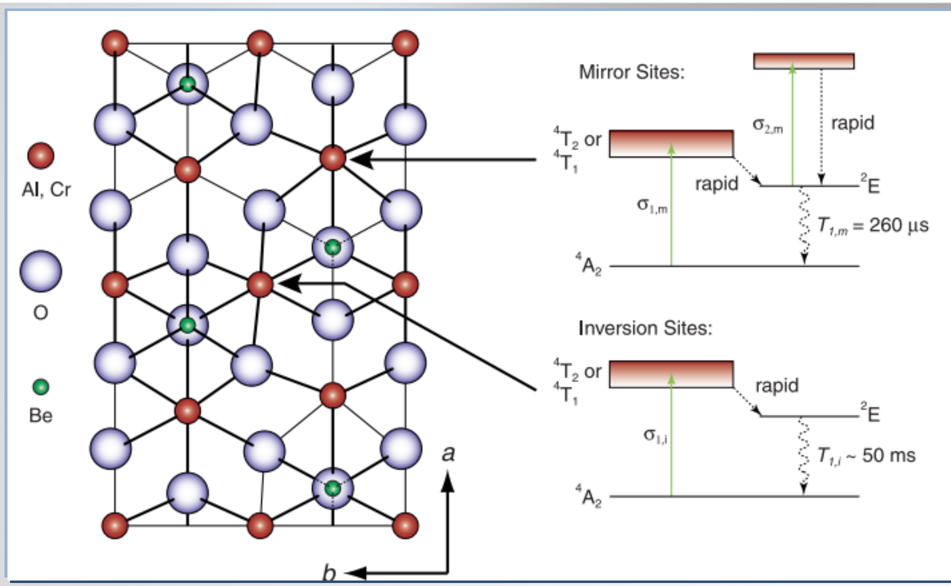
安徽理工大学 力学与光电物理学院

一、背景介绍

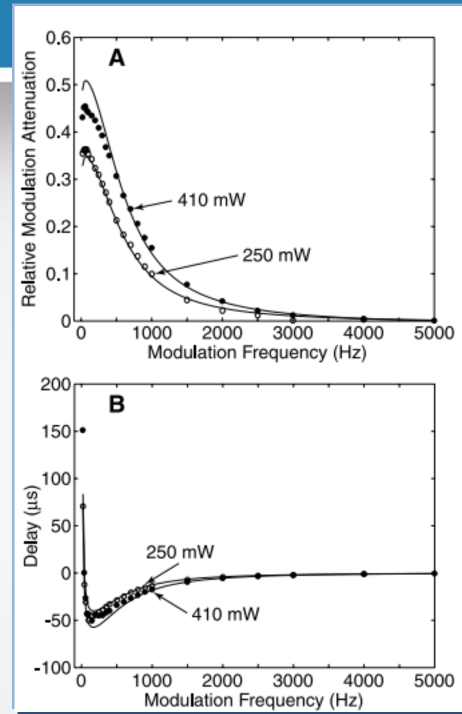


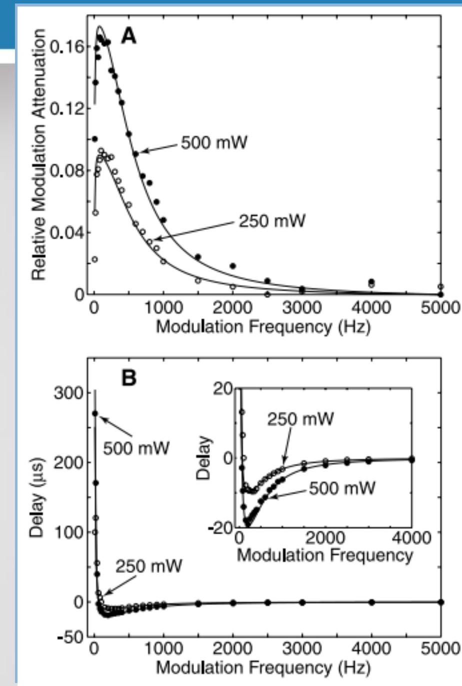
Lee D, Lee K W, Cady J V, et al. Topical review: spins and mechanics in diamond. Journal of Optics, 2017, 19(3): 033001.

一、背景介绍



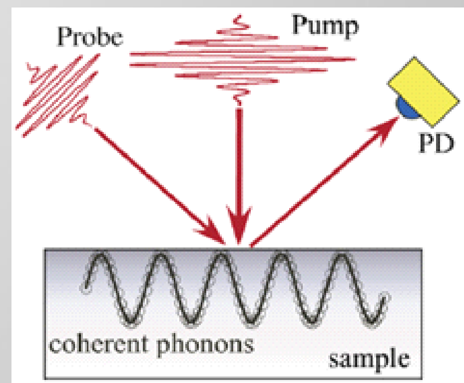
Bigelow, M. S., Lepeshkin, N. N., & Boyd, R. W. (2003). Superluminal and slow light propagation in a room-temperature solid. *Science*, *301*(5630), 200-202. 翠绿宝石晶体





Group velocity υ_g $\upsilon_g \ll c$ 慢光 $\upsilon_g > c$ 快光

$$\upsilon_g = \frac{c}{n_g} \qquad n_g = n + \omega_s \frac{dn}{d\omega_s} \longrightarrow \upsilon_g = \frac{c}{n + \omega_s (dn/d\omega_s)}$$

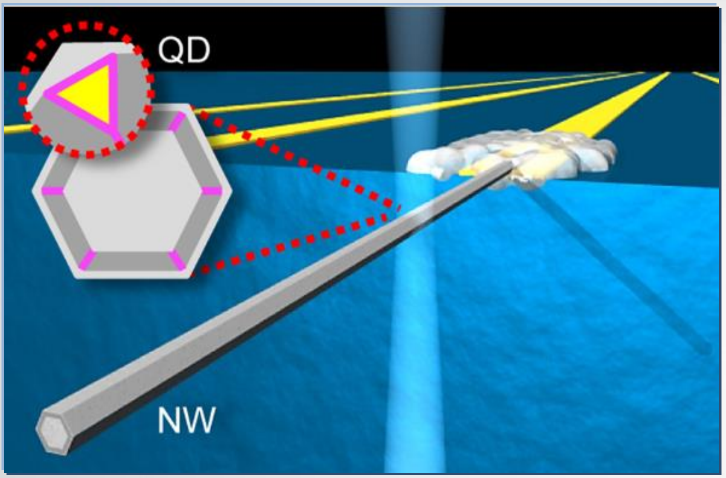


慢光产生机制： 电磁诱导透明、相干布居数振荡、受激布里渊散射、声子诱导透明

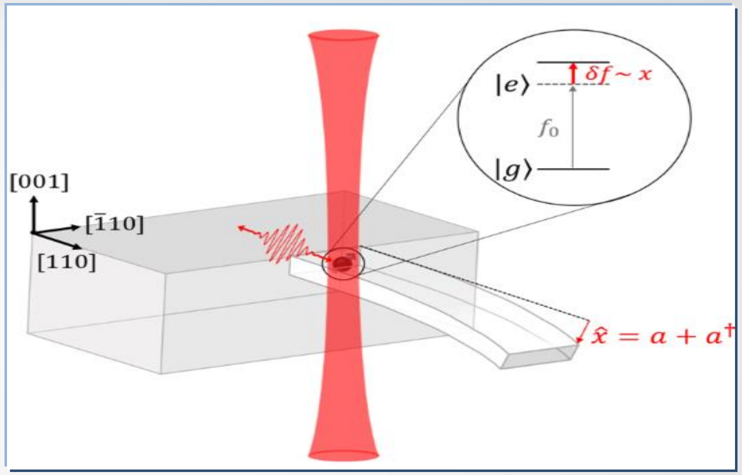
Boyd, R. W., & Gauthier, D. J. (2009). Controlling the velocity of light pulses. *science*, *326*(5956), 1074-1077.

二、混合量子系统

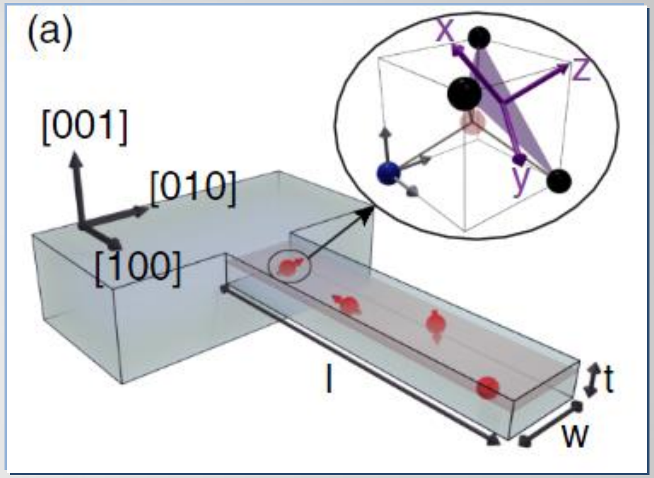
Strain Coupling of a Mechanical Resonator to a Single Quantum Emitter



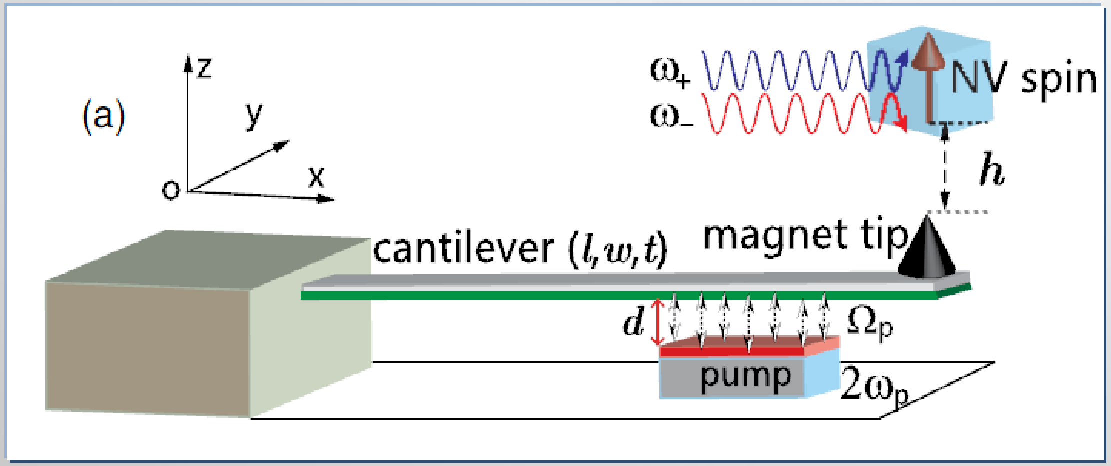
Montinaro, M. et al. Nano letters 14.8 (2014): 4454-4460.



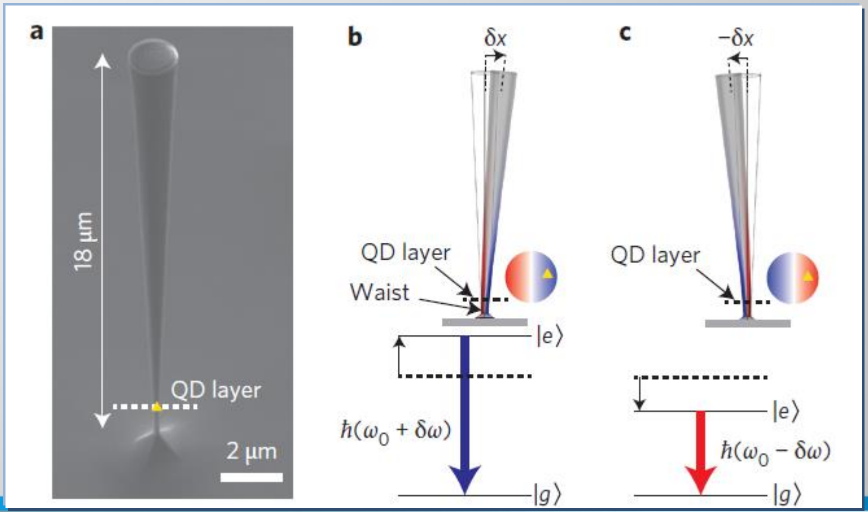
Lee, Kenneth W., et al Physical Review Applied 6 (2016): 034005.



Teissier, J., et al. Physical review letters 113.2 (2014): 020503.

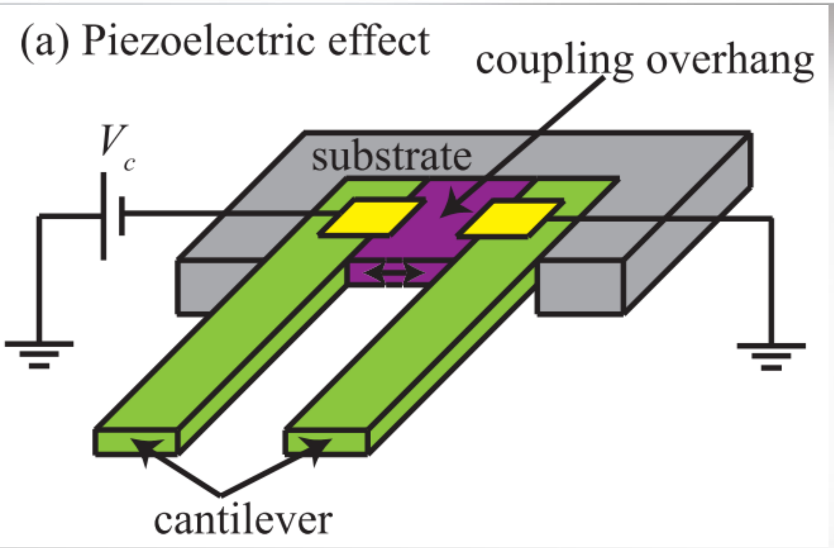


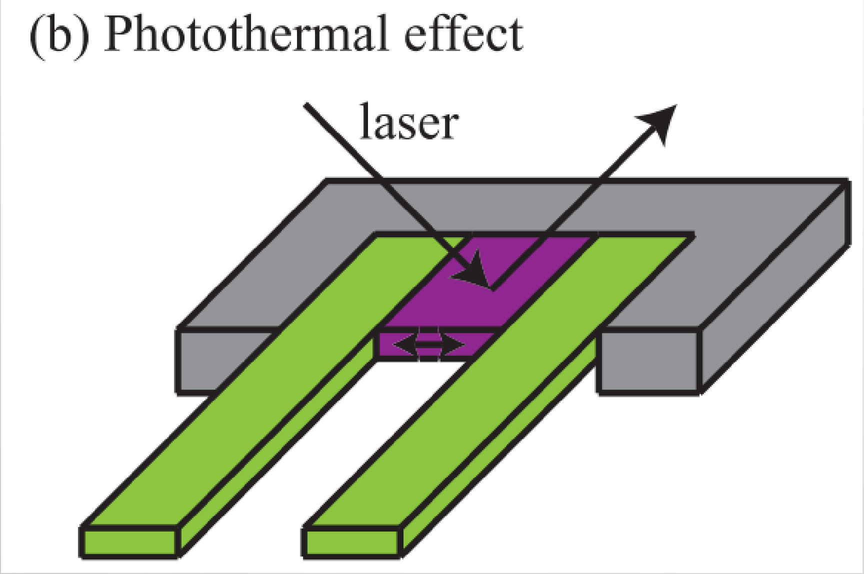
Li, Peng-Bo, et al. "Enhancing spin-phonon and spin-spin interactions using linear resources in a hybrid quantum system." Physical Review Letters 125.15 (2020): 153602.

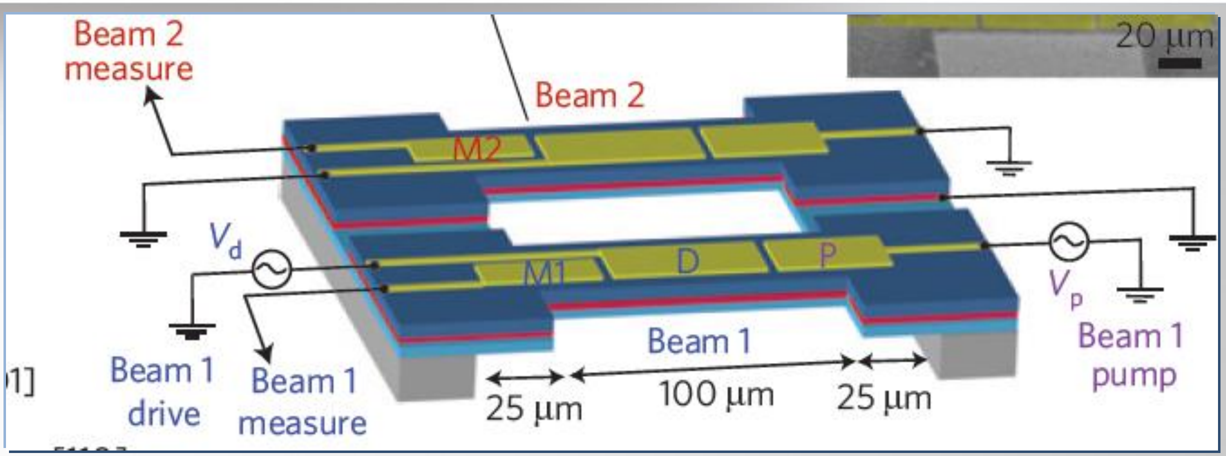


Yeo, Inah, et al. "Strain-mediated coupling in a quantum dot–mechanical oscillator hybrid system." Nature nanotechnology 9.2 (2014): 106-110.

Mechanical mode coupling



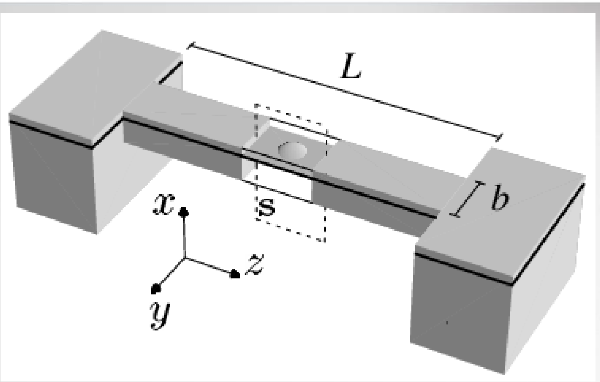




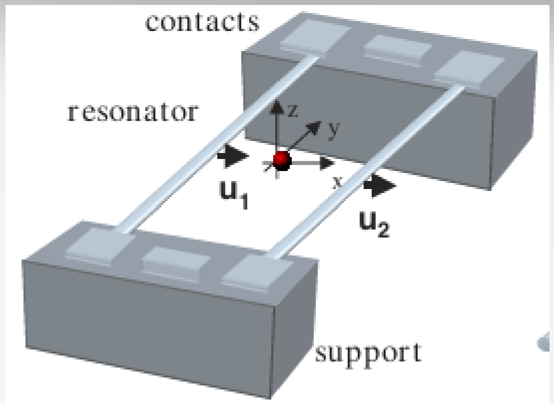
Okamoto, Hajime, et al. "Coherent phonon manipulation in coupled mechanical resonators." Nature Physics 9.8 (2013): 480-484.

In addition, the two vibrating mirrors can also be coupled through the electrostatic force or Coulomb interaction for charged vibrating mirrors.

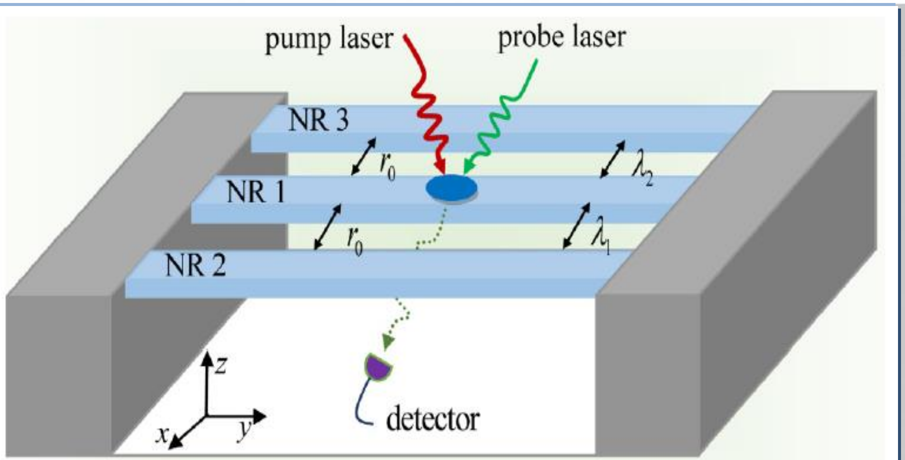
三、我的工作：复合纳米机械振子系统中的光学现象



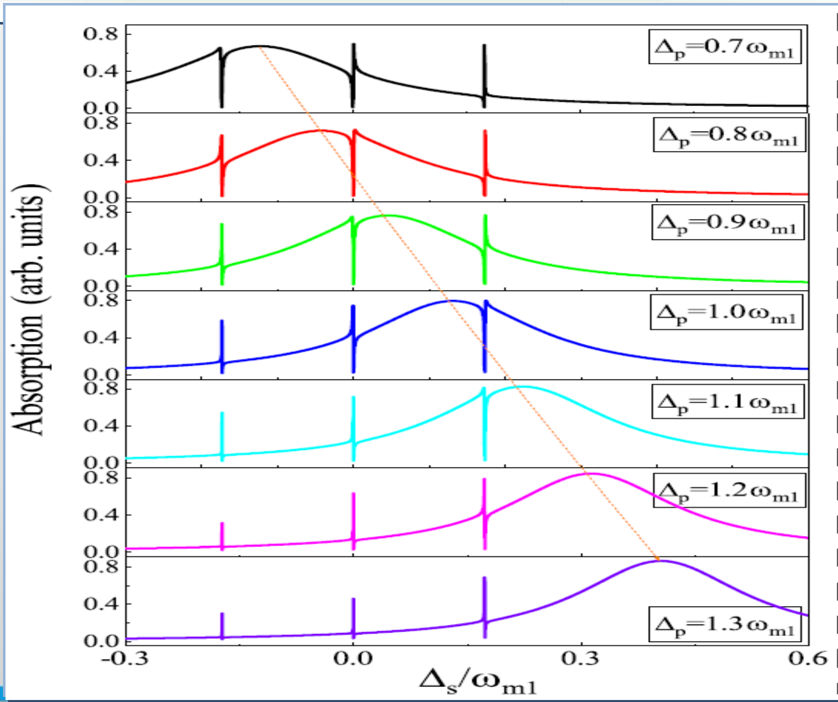
Wilson-Rae I, Zoller P, Imamoğlu A. Laser cooling of a nanomechanical resonator mode to its quantum ground state[J]. Physical review letters, 2004, 92(7): 075507.



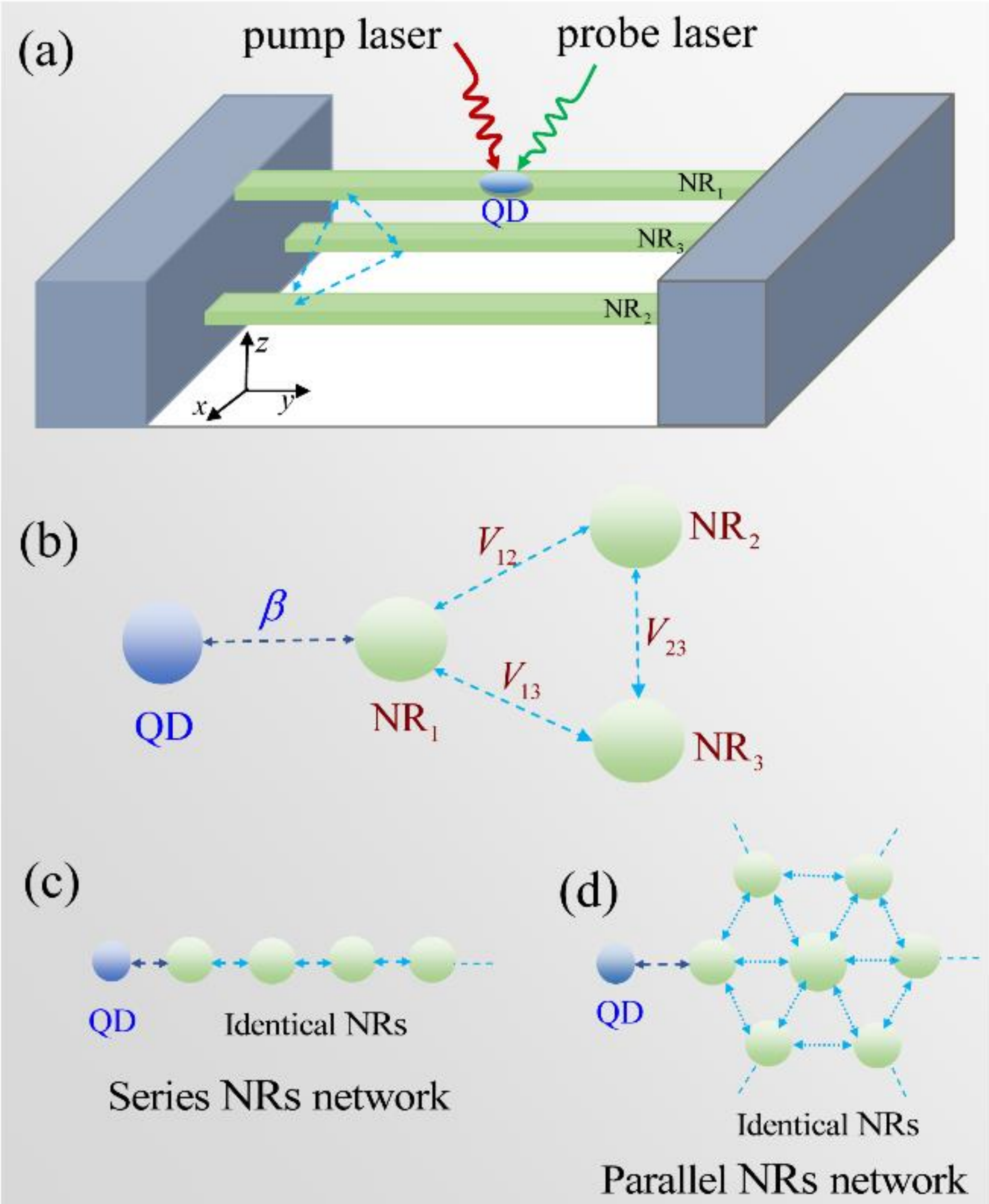
Tian L, Zoller P. Coupled ion-nanomechanical systems[J]. Physical review letters, 2004, 93(26): 266403.

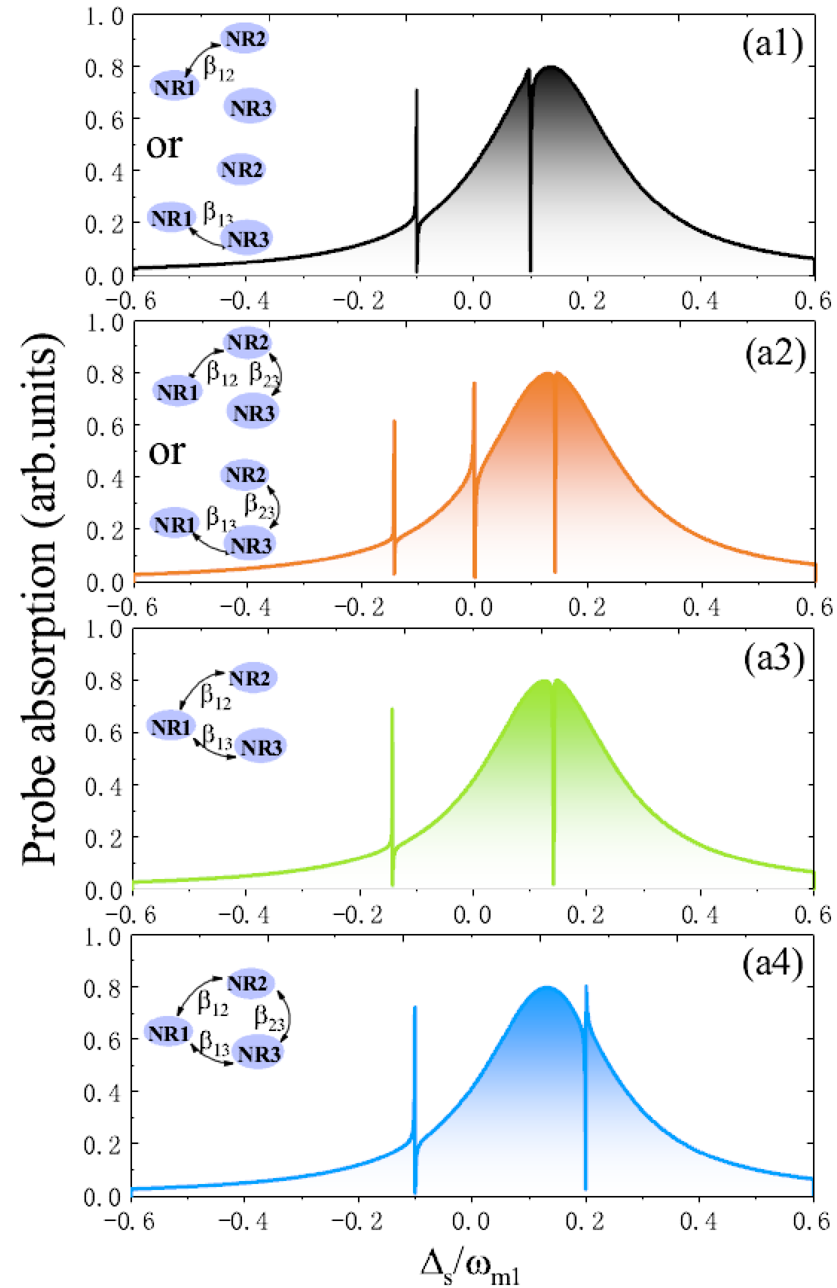


$$
\begin{aligned}
H = & \hbar\omega_{ex}S^z + \hbar\omega_{m1}a_1^\dagger a_1 + \hbar\omega_{m2}a_2^\dagger a_2 + \hbar\omega_{m3}a_3^\dagger a_3 \\
& + \hbar\omega_{m1}\beta S^z(a_1^\dagger + a_1) + \hbar\lambda_1(a_1^\dagger a_2 + a_1 a_2^\dagger) \\
& + \hbar\lambda_2(a_1^\dagger a_3 + a_1 a_3^\dagger) - \mu\varepsilon_p(S^\dagger e^{-i\omega_p t} + S^- e^{i\omega_p t}) \\
& - \mu\varepsilon_s(S^\dagger e^{-i\omega_s t} + S^- e^{i\omega_s t}),
\end{aligned}
$$



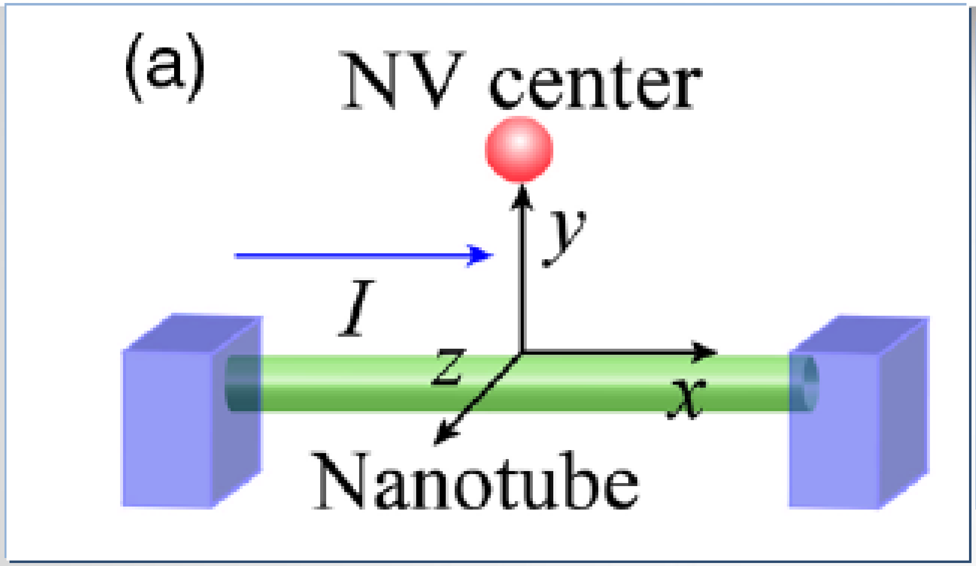
Hua-Jun Chen. "Multiple-Fano-resonance-induced fast and slow light in the hybrid nanomechanical-resonator system." Physical Review A 104.1 (2021): 013708.



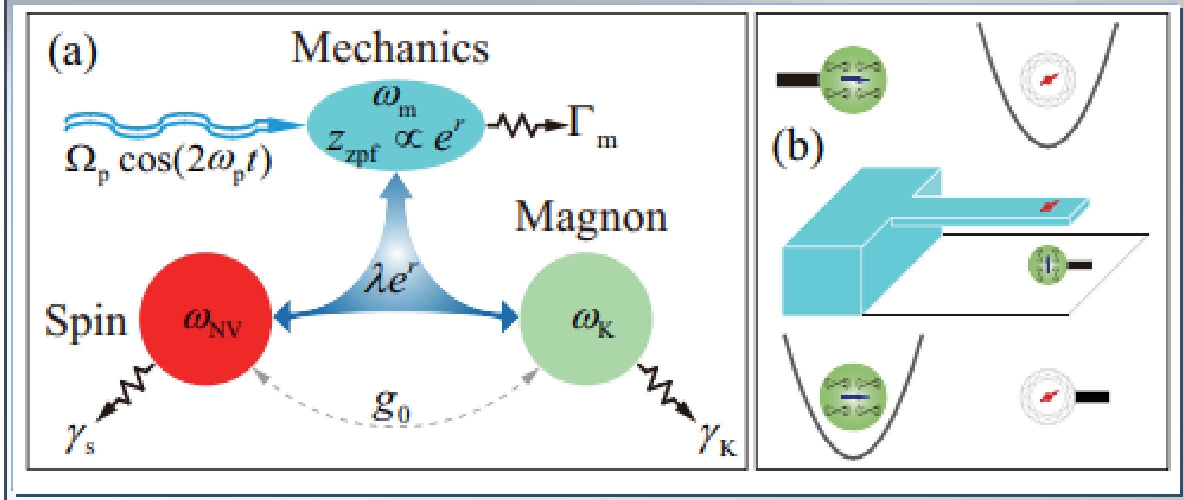


Hua-Jun Chen. "The fast–slow light transitions induced by Fano resonance in multiple nanomechanical resonators." Optics & Laser Technology 161 (2023): 109242.

金刚石空位自旋-机械振子系统(强耦合)



Li, Peng-Bo, et al. "Hybrid quantum device with nitrogen-vacancy centers in diamond coupled to carbon nanotubes." Physical review letters 117.1 (2016): 015502.



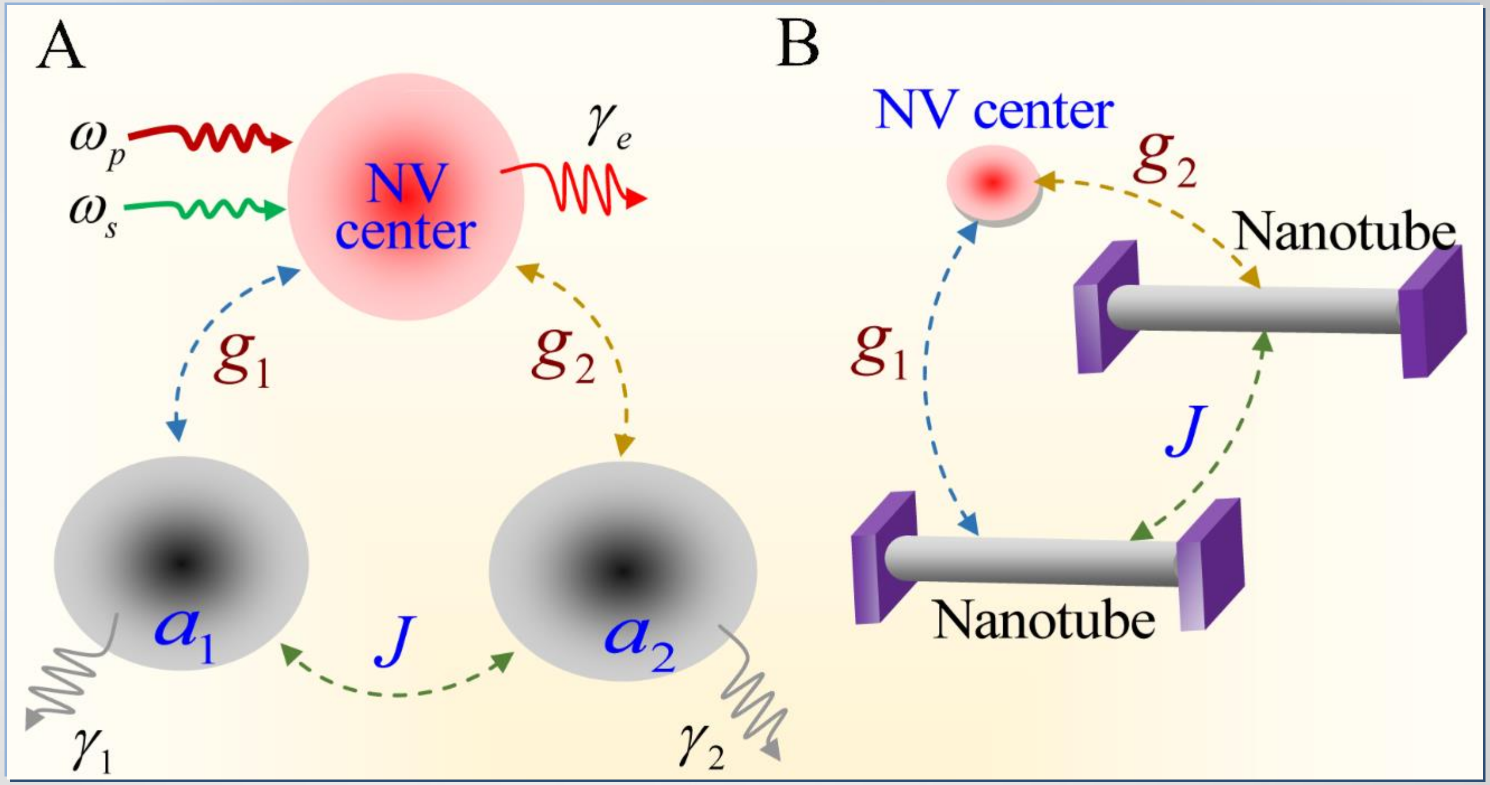
Hei X L, Li P B, Pan X F, et al. Enhanced tripartite interactions in spin-magnon-mechanical hybrid systems. Physical Review Letters, 2023, 130(7): 073602.

The coupling of NV spins between mechanical resonators can be achieved extrinsically (external **magnetic field gradients**) or intrinsically (mechanical strain).

NV自旋：即使在室温下，相干时间也很长

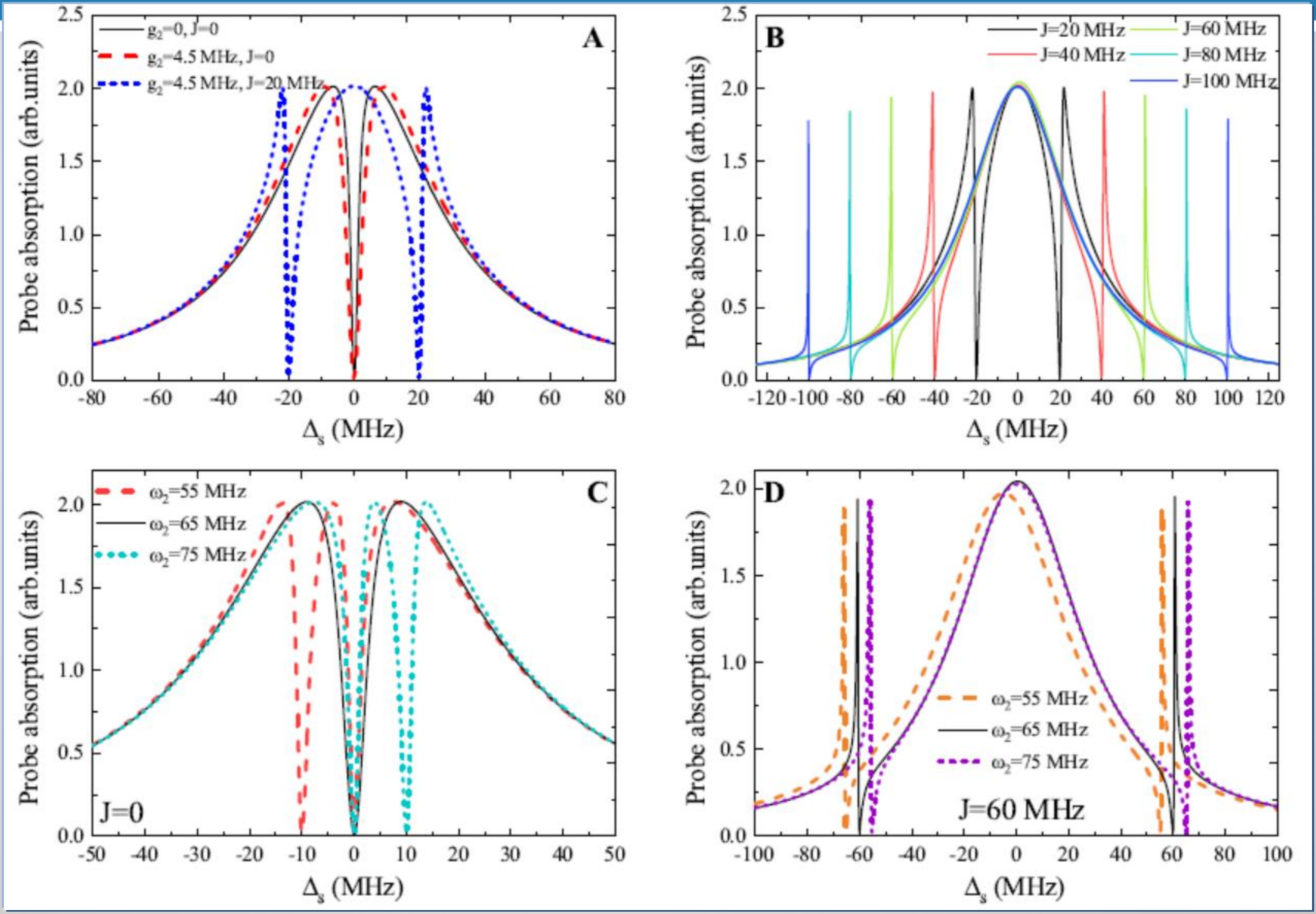
碳纳米管振子：超低质量，超高和广泛可调的频率，以及超高Q因子

双色电磁诱导透明现象



$$
\begin{aligned}
H &= H_{CNT} + H_{NV} + H_{S-R} + H_{int} + H_{dri} \\
&= \sum_{k=1,2} \hbar\omega_k a_k^\dagger a_k + \frac{1}{2}\hbar\Delta_p\sigma^z + \sum_{k=1,2} \hbar g_k (a_k^\dagger\sigma^- + a_k\sigma^+) + \hbar J (e^{i\theta} a_1^\dagger a_2 + e^{-i\theta} a_1 a_2^\dagger) \\
&\quad -\hbar\Omega_p(\sigma^+ + \sigma^-) - \mu\varepsilon_s(\sigma^+ e^{-i\delta t} + \sigma^- e^{i\delta t}),
\end{aligned}
$$

Hua-Jun Chen. Two-color electromagnetically induced transparency generated slow light in double-mechanical-mode coupling carbon nanotube resonators. iScience, 2024, 27: 109328;



A
g2=0, J=0
g2=4.5 MHz, J=0
g2=4.5 MHz, J=20 MHz
B
J=20 MHz
J=40 MHz
J=60 MHz
J=80 MHz
J=100 MHz
C
ω2=55 MHz
ω2=65 MHz
ω2=75 MHz
J=0
D
ω2=55 MHz
ω2=65 MHz
ω2=75 MHz
J=60 MHz
Probe absorption (arb.units)
Δs (MHz)

In the condition of the strong-driving regime, i.e., the pump field is more stronger than the probe field, according to the linearized Langevin equations of Equation 9 to Equation 11, the Hamiltonian in the rotating-wave approximation [16, 17] is ($\hbar = 1$)

$$\begin{aligned} H_{RWA} &= \frac{1}{2}\Delta_p \delta\sigma^z + \omega_1 \delta a_1^\dagger \delta a_1 + \omega_2 \delta a_2^\dagger \delta a_2 + g_1(\delta a_1^\dagger \delta\sigma^- + \delta a_1 \delta\sigma^+) + g_2(\delta a_2^\dagger \delta\sigma^- + \delta a_2 \delta\sigma^+) \\ &+ J(e^{i\theta}\delta a_1^\dagger \delta a_2 + e^{-i\theta}\delta a_1 \delta a_2^\dagger). \end{aligned} \tag{16}$$

In order to investigate the role of phonon-exchange interaction, two bosonic modes $\tilde{A}_+$ and $\tilde{A}_-$ are introduced as following

$$\tilde{A}_+ = f\delta a_1 - e^{i\theta} h\delta a_2, \quad \tilde{A}_- = e^{-i\theta} h\delta a_1 + f\delta a_2, \tag{17}$$

then, the Hamiltonian of Equation 16 reduces to

$$H_{RWA} = \frac{1}{2}\Delta_p \delta\sigma^z + \tilde{\omega}_+ \tilde{A}_+^\dagger \tilde{A}_+ + \tilde{\omega}_- \tilde{A}_-^\dagger \tilde{A}_- + \tilde{g}_+(\delta\sigma^- \tilde{A}_+^\dagger + \tilde{A}_+ \delta\sigma^+) + \tilde{g}_-(\delta\sigma^- \tilde{A}_-^\dagger + \tilde{A}_- \delta\sigma^+), \tag{18}$$

where resonance frequencies and coupling strengths are as follows

$$\tilde{\omega}_\pm = \frac{1}{2}(\omega_1 + \omega_2) \pm \sqrt{(\omega_1 - \omega_2)^2 + 4J^2}, \tag{19}$$

$$\tilde{g}_+ = fg_1 - e^{i\theta} hg_2, \quad \tilde{g}_- = e^{-i\theta} hg_1 + fg_2, \tag{20}$$

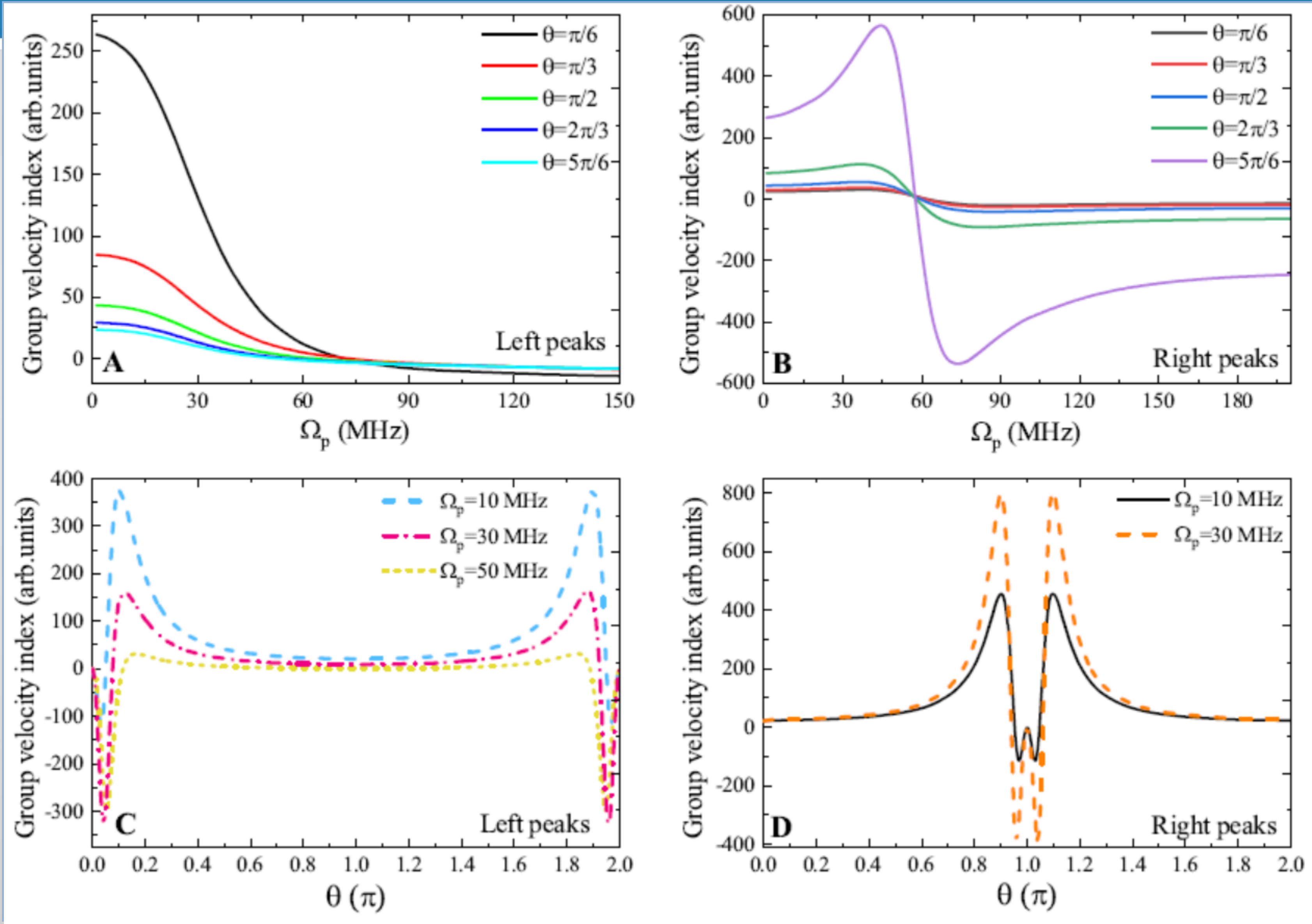
with the two parameters of

$$f = \frac{|\tilde{\omega}_- - \omega_1|}{\sqrt{(\tilde{\omega}_- - \omega_1)^2 + J^2}}, \quad h = \frac{Jf}{\tilde{\omega}_- - \omega_1}. \tag{21}$$

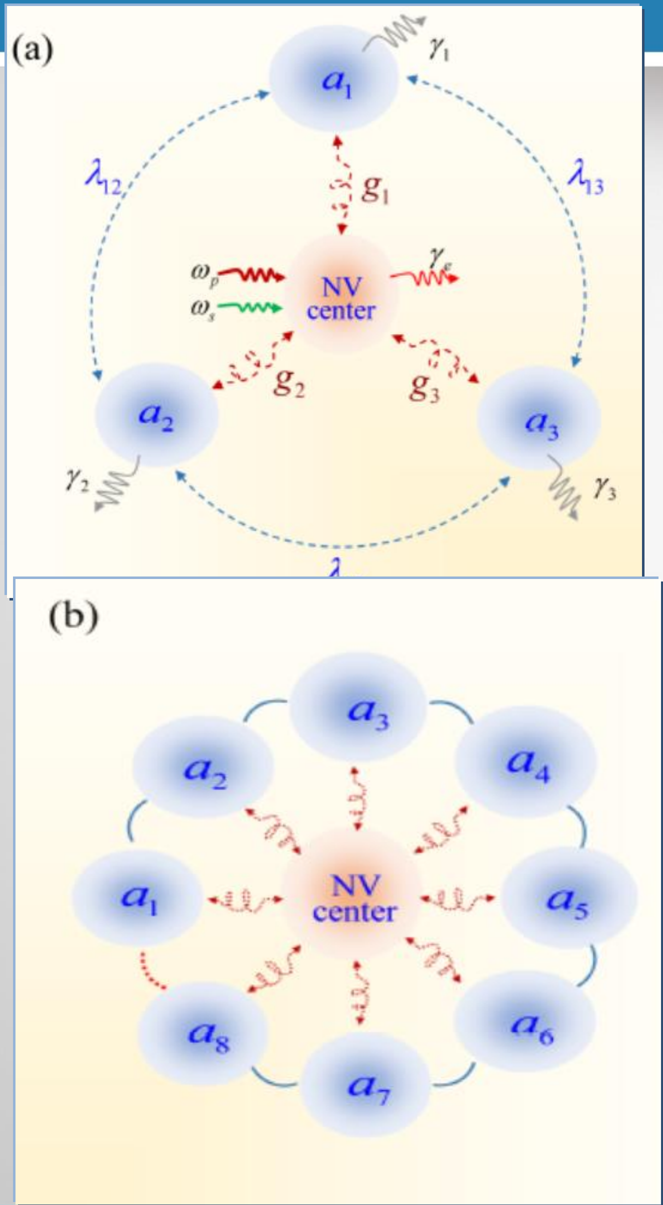
When the two mechanical modes have the same frequencies, $\omega_1 = \omega_2$, and coupling strengths, $g_1 = g_1 = g$, the coupling strengths in Equation 20 can be simplified as

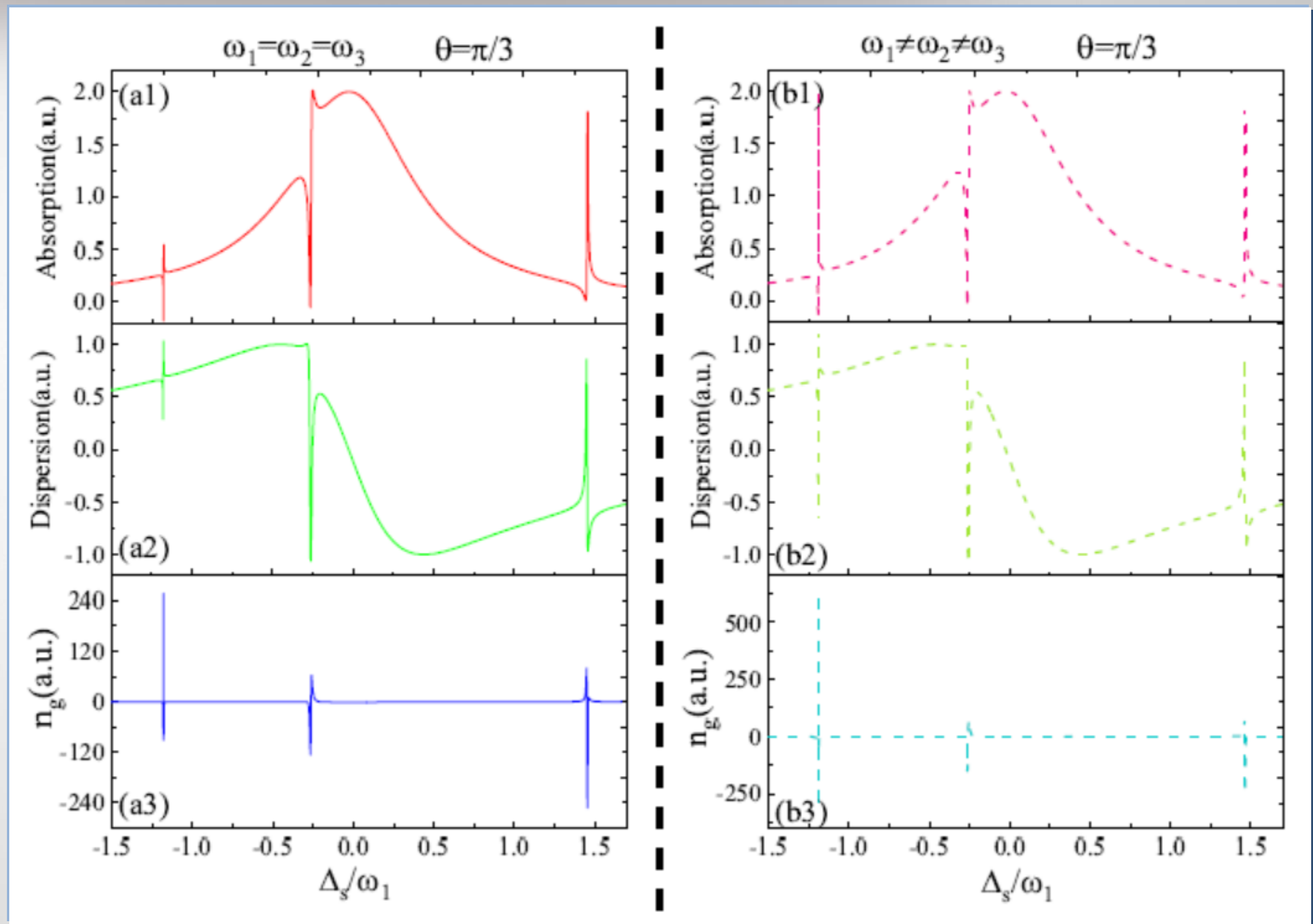
$$\tilde{g}_+ = \frac{\sqrt{2}g(1 + e^{-i\theta})}{2}, \quad \tilde{g}_- = \frac{\sqrt{2}g(1 - e^{-i\theta})}{2}. \tag{22}$$

In Equation 22, when $\theta = n\pi$ for an integer n, the spin mode is decoupled from one of the two hybridized mechanical modes $\tilde{A}_-$ (for an even number n) and $\tilde{A}_+$ (for an odd number n). These features mean that the dark-mode effect can be broken by tuning the modulation phase $\theta \neq n\pi$.

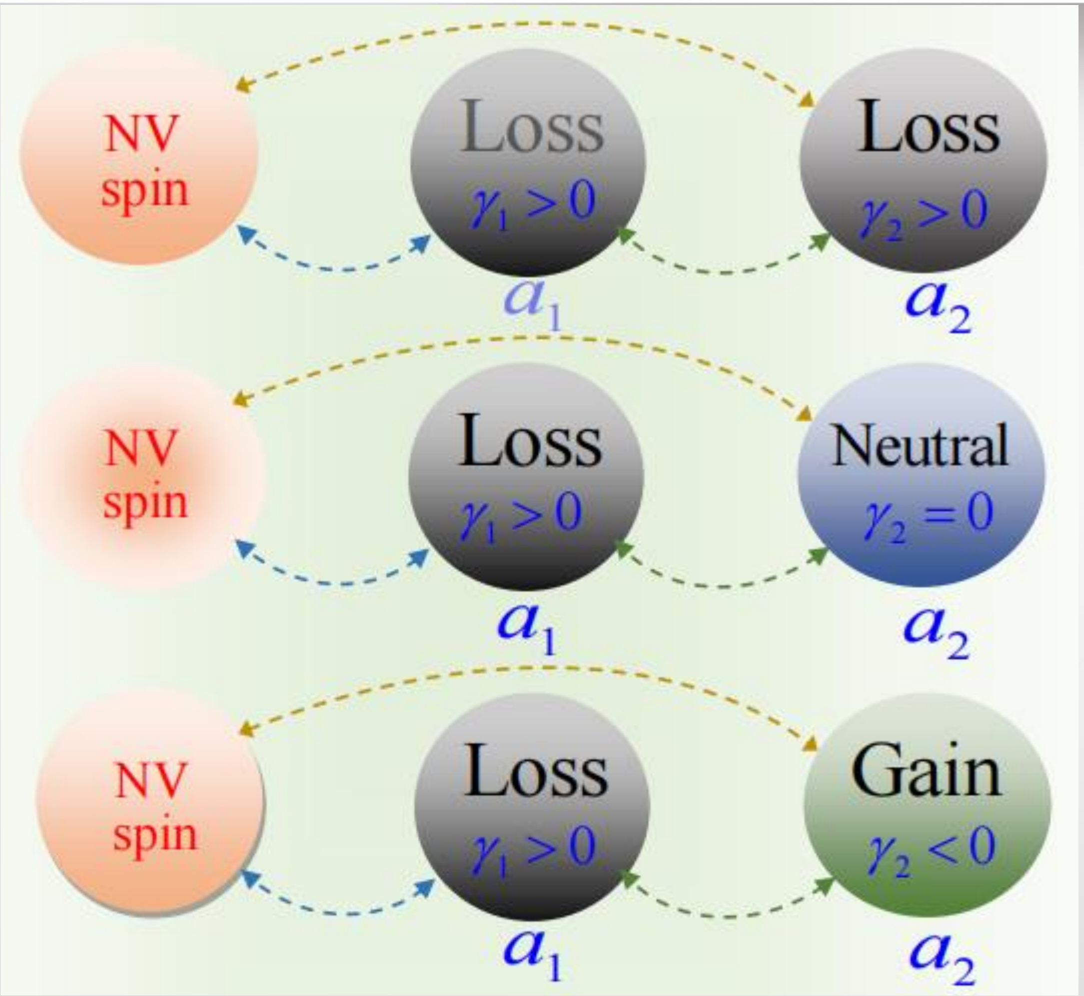


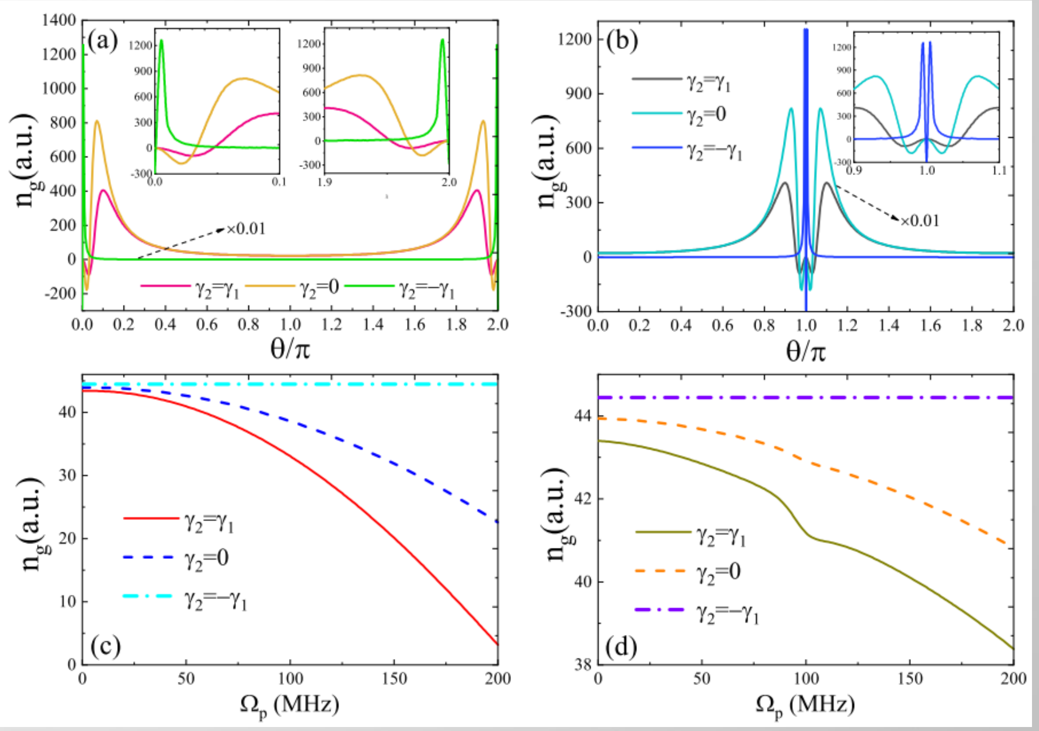
Group velocity index (arb.units)
θ=π/6
θ=π/3
θ=π/2
θ=2π/3
θ=5π/6
Left peaks
A
Ωp (MHz)
Right peaks
B
Ωp=10 MHz
Ωp=30 MHz
Ωp=50 MHz
C
θ (π)
D





Hua-Jun Chen. Triple electromagnetically induced transparency generated slow light for multiple carbon nanotube resonators. Journal of Applied Physics, 135, 074401 (2024)


NV spin
Loss $\gamma_1>0$
Loss $\gamma_2>0$
a_1
a_2
NV spin
Loss $\gamma_1>0$
Neutral $\gamma_2=0$
a_1
a_2
NV spin
Loss $\gamma_1>0$
Gain $\gamma_2<0$
a_1
a_2


(a)
(b)
(c)
(d)
n_g(a.u.)
θ/π
Ω_p (MHz)
×0.01
×0.01
$\gamma_2=\gamma_1$
$\gamma_2=0$
$\gamma_2=-\gamma_1$

谢谢！