Australian National University

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY

AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Photothermal Effects, Optomechanics and Optical Levitation

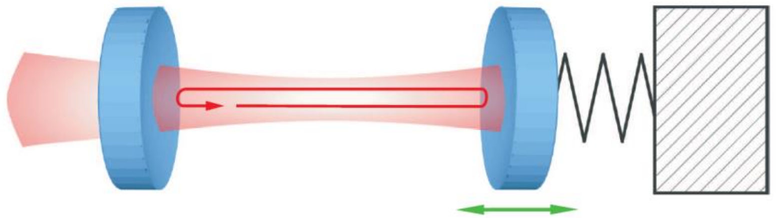
Chenyue Gu

Supervisors: Jiayi Qin, Giovanni Guccione, and Ping Koy Lam

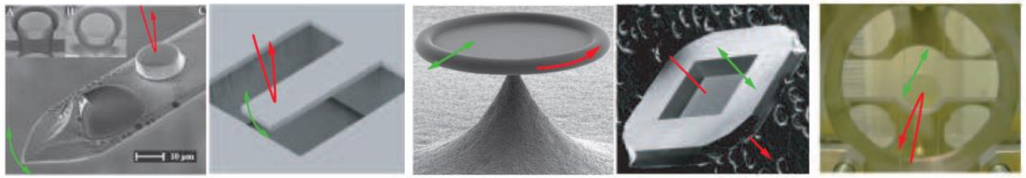
Introduction

Cavity optomechanics

(a)



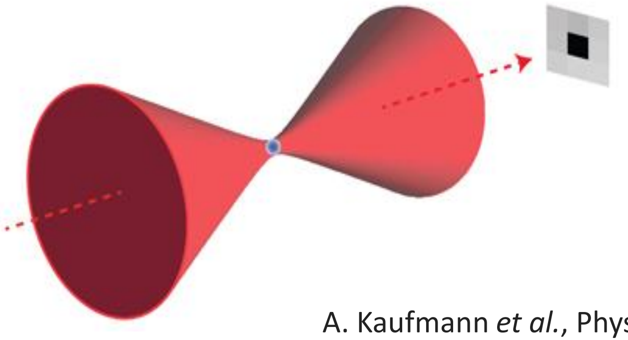
(b)



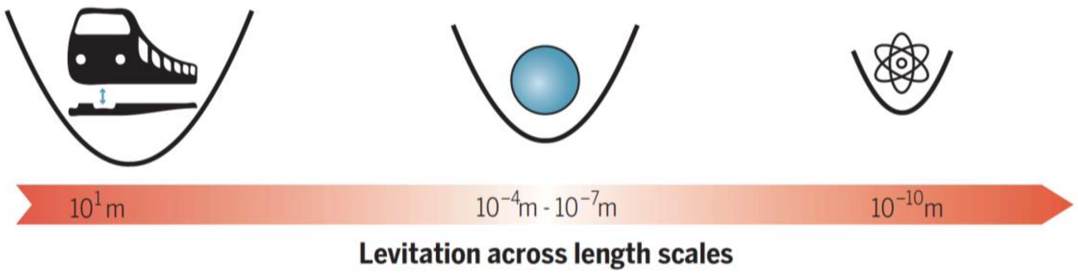
$\mathcal{F}$	200	30,000	22,000	15,000	4,000
$\Omega_m/2\pi$	12.5 kHz	814 kHz	57.8 MHz	134 kHz	12.7 Hz
Q_m	18,400	10,000	2,900	$1.1 \cdot 10^6$	19,950
m_{eff}	24 ng	190 μg	15 ng	40 ng	~1 g
Ref.	[34]	[26,27]	[22,28]	[30]	[29]

[2] Kippenberg, T. J., & Vahala, K. J. (2007). Cavity opto-mechanics. Optics express, 15(25), 17172-17205.

Optical levitation



A. Kaufmann *et al.*, Phys. Rev. X (2012)

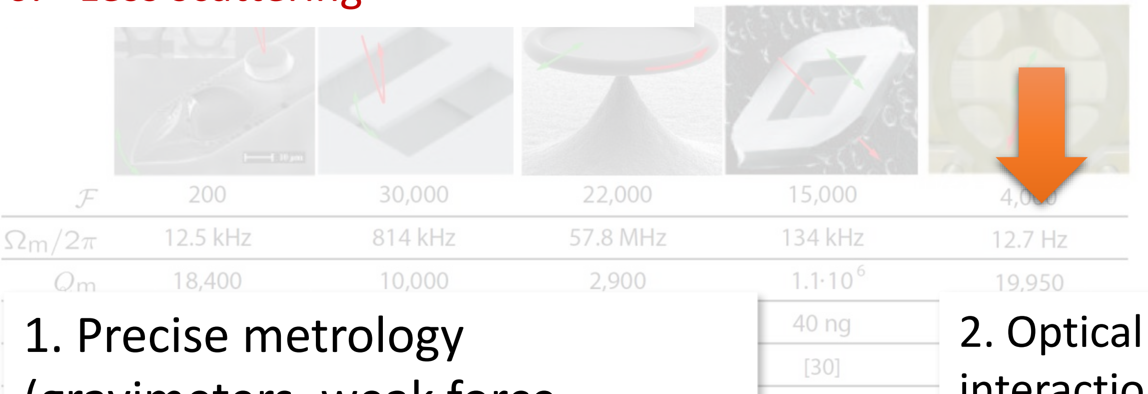


[3] Gonzalez-Ballestero, C., Aspelmeyer, M., Novotny, L., Quidant, R., & Romero-Isart, O. (2021). Levitodynamics: Levitation and control of microscopic objects in vacuum. Science, 374(6564), eabg3027.

Introduction

Cavity optomechanics

1. High sensitivity
2. Tunability (Optical spring)
3. Simultaneously readout
4. Robustness to mechanical loss
5. Can deal with mass
6. Less scattering



1. Precise metrology (gravimeters, weak force, pressure sensors, acceleration & rotation sensors)

chanics. Optics express,

Optical levitation

1. High inertial sensitivity
2. Tunability (external degree of freedom)
3. Coupling internal and external degree of freedom
4. Simultaneously readout
5. Free to move
6. Controllable isolation

2. Optical and mechanical interaction

3. Preparation of mechanical quantum states

[3] Gonzalez-Ballestero, C., Aspelmeyer, M., Novotny, L., Quidant, R., & Romero-Isart, O. (2021). Levitodynamics: Levitation and control of microscopic objects in vacuum. Science, 374(6564), eabg3027.

Optomechanical Levitation

1. Environmental isolation

2. Scattering-free

3. Large mass

4. Simultaneous optical readouts

Mass : 1.116 mg
Size : diameter ~3 mm
thickness ~50 μm

Optomechanical Levitation

Australian National University

Mass : 1.116 mg
Size : diameter ~3 mm
thickness ~50 μm

1. Optomechanics

2. Optical-levitation System and Current Model

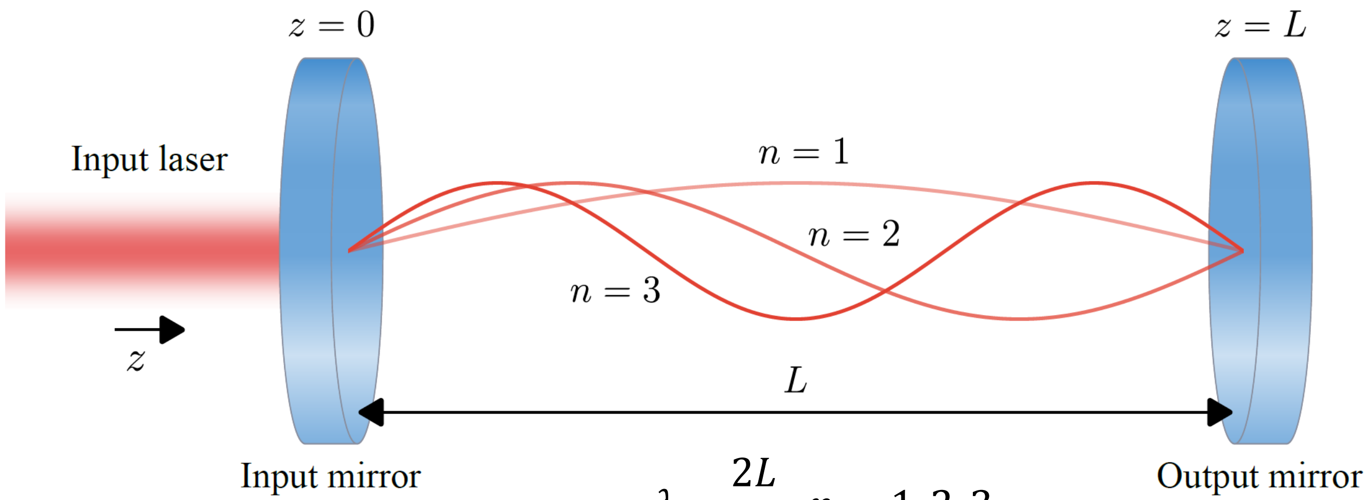
3. Photothermal Cancellation

4. Model with multiple photothermal effects

Optomechanical Levitation

1. Optomechanics
2. Optical-levitation System and Current Model
3. Photothermal Cancellation
4. Model with multiple photothermal effects

Optomechanics



$\lambda = \frac{2L}{n}$, $n = 1, 2, 3, \ldots$

Resonance frequencies: $\omega_{cav,n} = \frac{n\pi c}{L}$

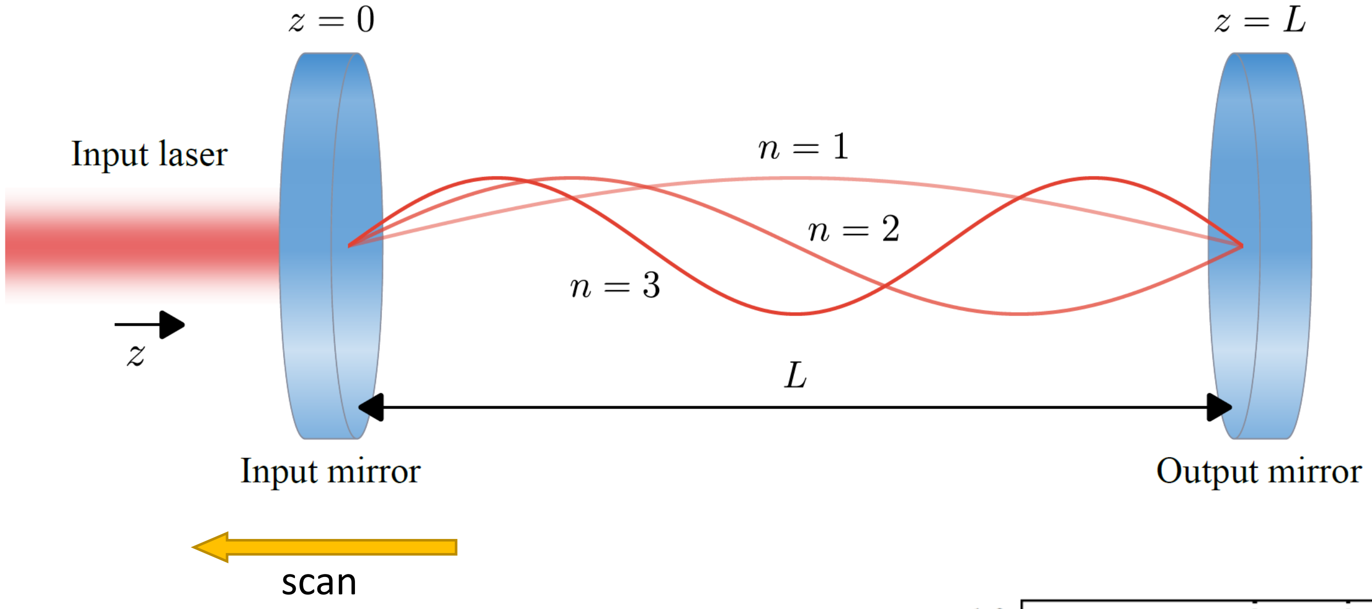
Free spectral range (FSR): $\Delta\omega_{FSR} = \omega_{cav,n} - \omega_{cav,n-1} = \frac{\pi c}{L}$

Cavity loss: $\kappa = \kappa_{in} + \kappa_{out} + \kappa_0$

Finesse: $\mathcal{F} \equiv \frac{\Delta\omega_{FSR}}{\kappa}$

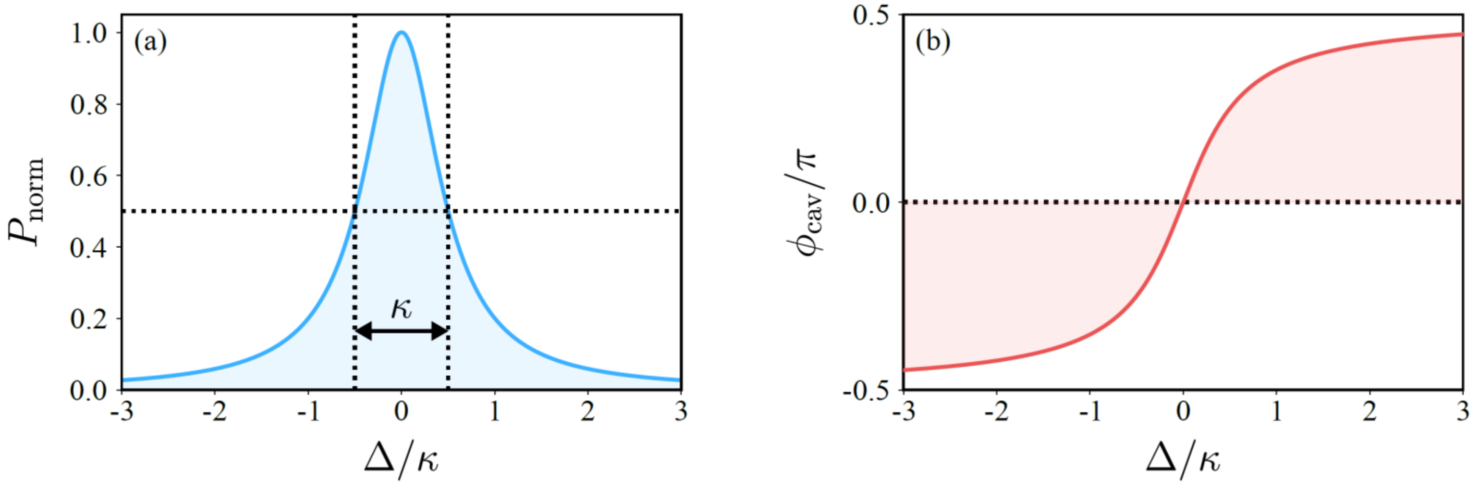
Optomechanics

Australian National University

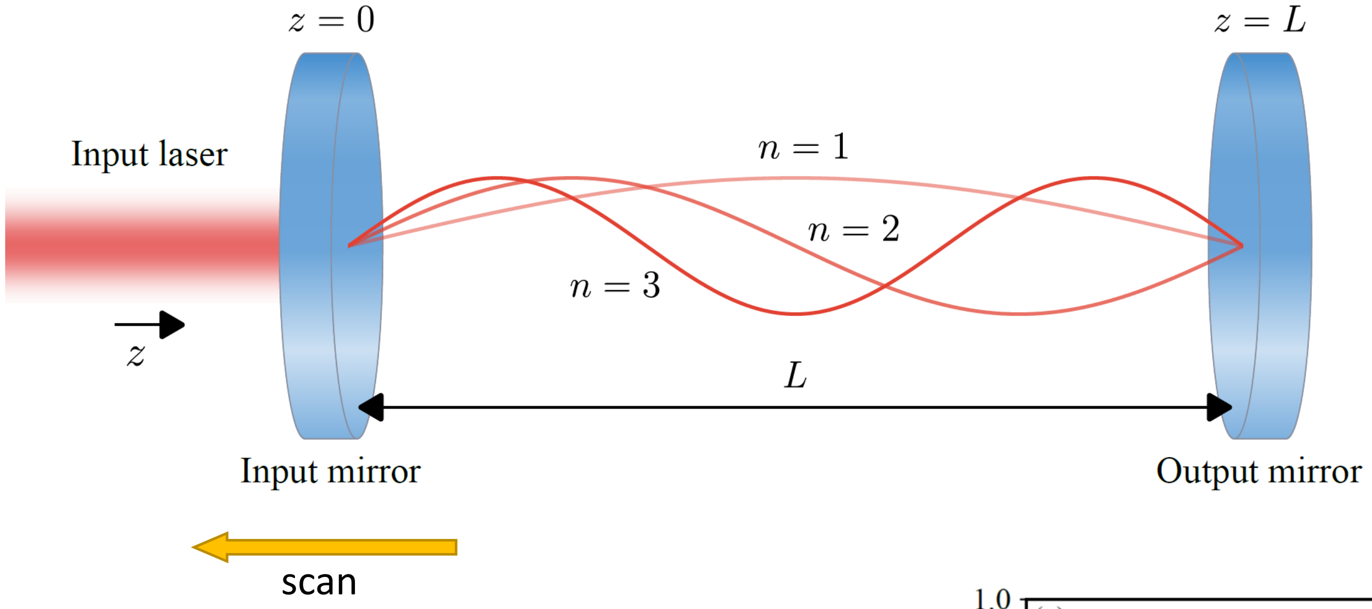


$$\dot{a} = -(\frac{\kappa}{2} - i\Delta)a + \sqrt{\kappa_{in}}a_{in}$$

$$\Delta = \omega_L - \omega_{cav}$$



Optomechanics



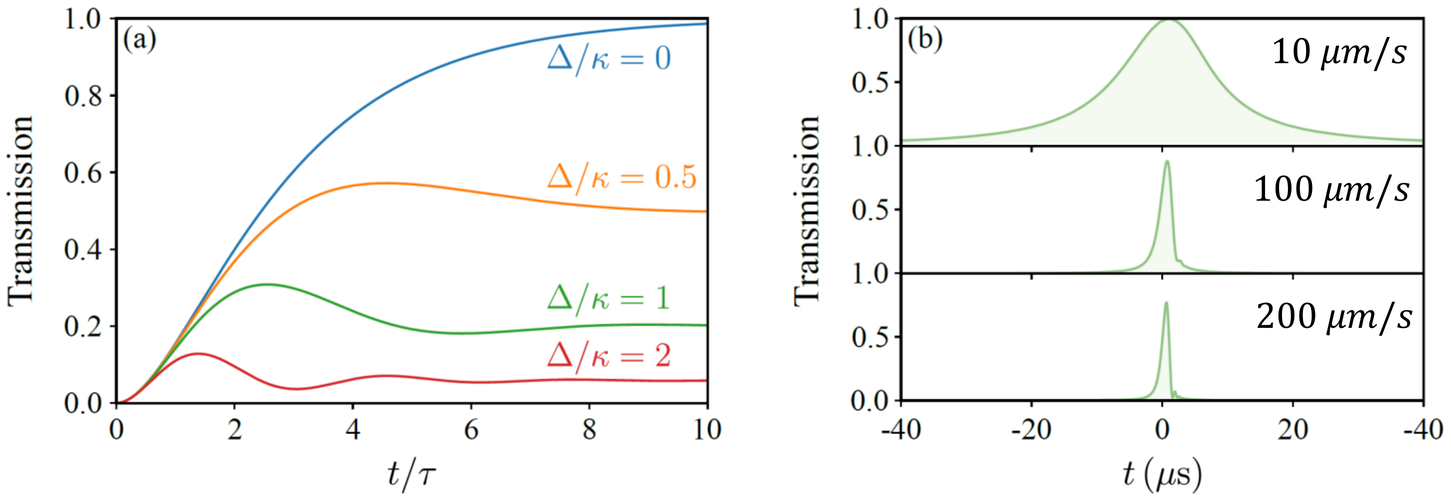
$$\dot{a} = -[\frac{\kappa}{2} - i\Delta(t)]a + \sqrt{\kappa_{in}}a_{in}$$

$$L(t) = L_0 + v_{scan}t$$

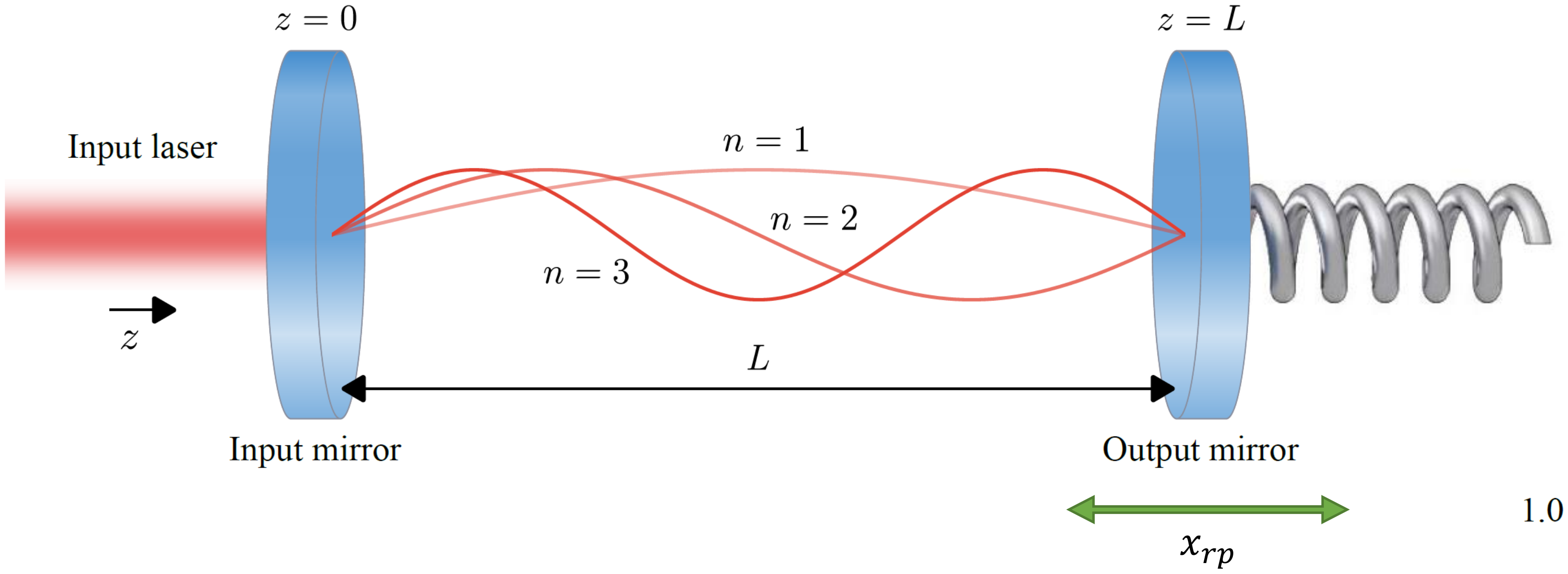
$$\Delta(t) = \Delta_0 + \frac{2kv_{scan}t}{\tau_{cav}}$$

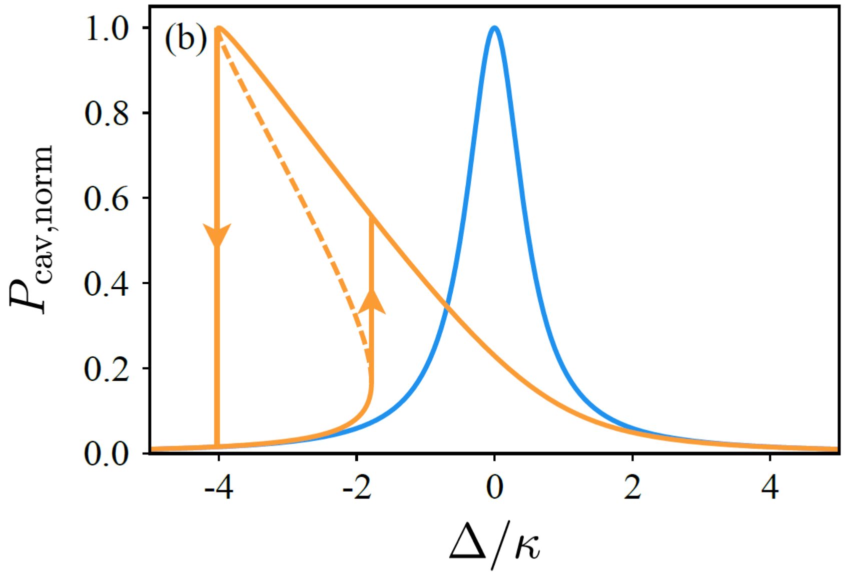
k: wavenumber

τ_{cav} : one-trip time



Optomechanics





$$\dot{a} = -[\frac{\kappa}{2} - i(\Delta + Gx_{rp})]a + \sqrt{\kappa_{in}}a_{in}$$

$$\ddot{x}_{rp} = -\Omega_m^2 x_{rp} - \Gamma_m \dot{x}_{rp} + F_{opt}(t)$$

G: frequency pull parameter
Ω_m: frequency
Γ_m : damping rate
$\mathrm{F}_{opt}(t)$: optical force

Optomechanical Levitation

Australian National University

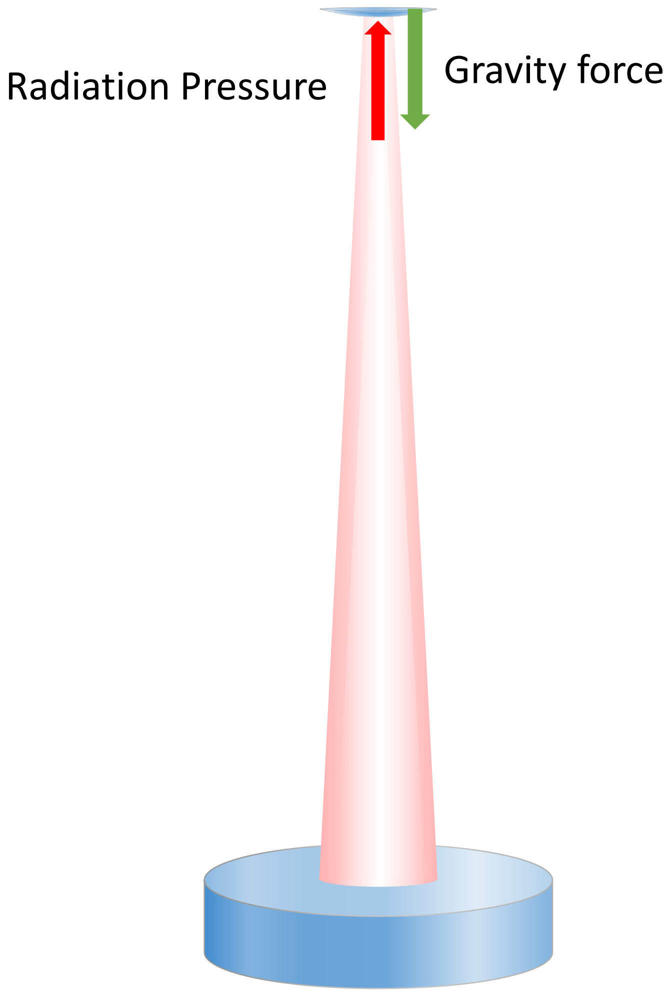
1. Optomechanics

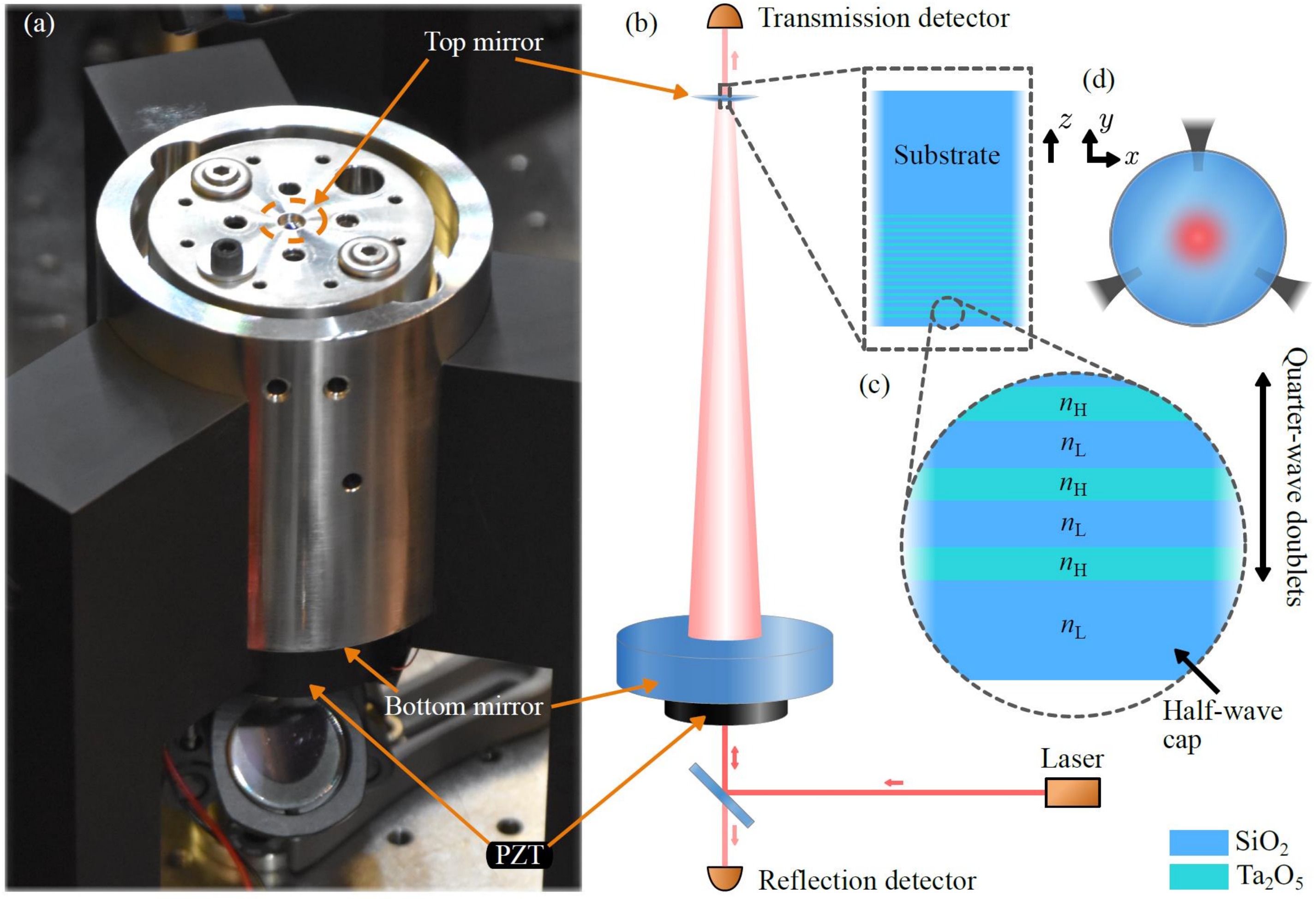
2. Optical-levitation System and Current Model

3. Photothermal Cancellation

4. Model with multiple photothermal effects

Optomechanical system





Optomechanical system

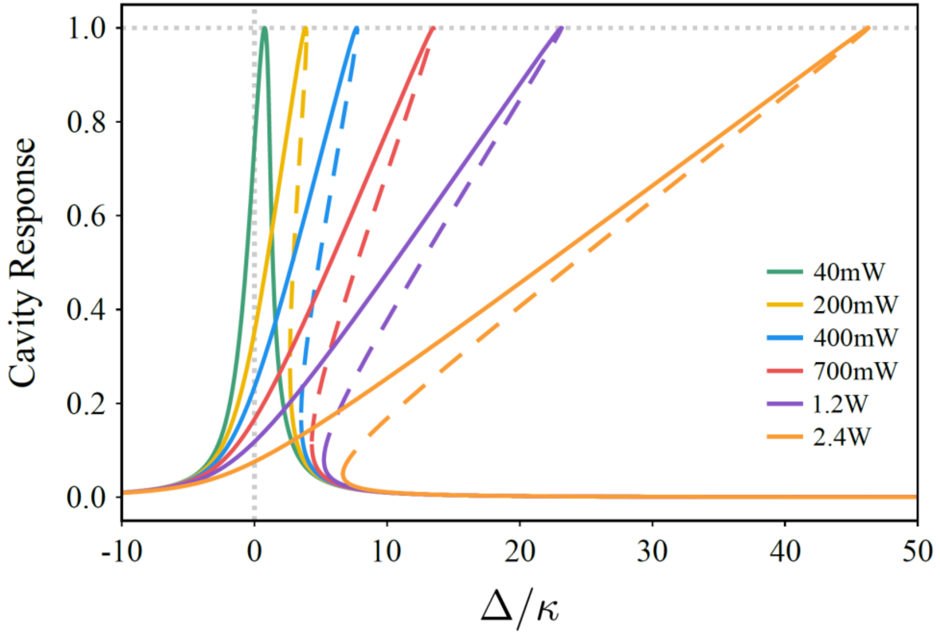
Australian National University

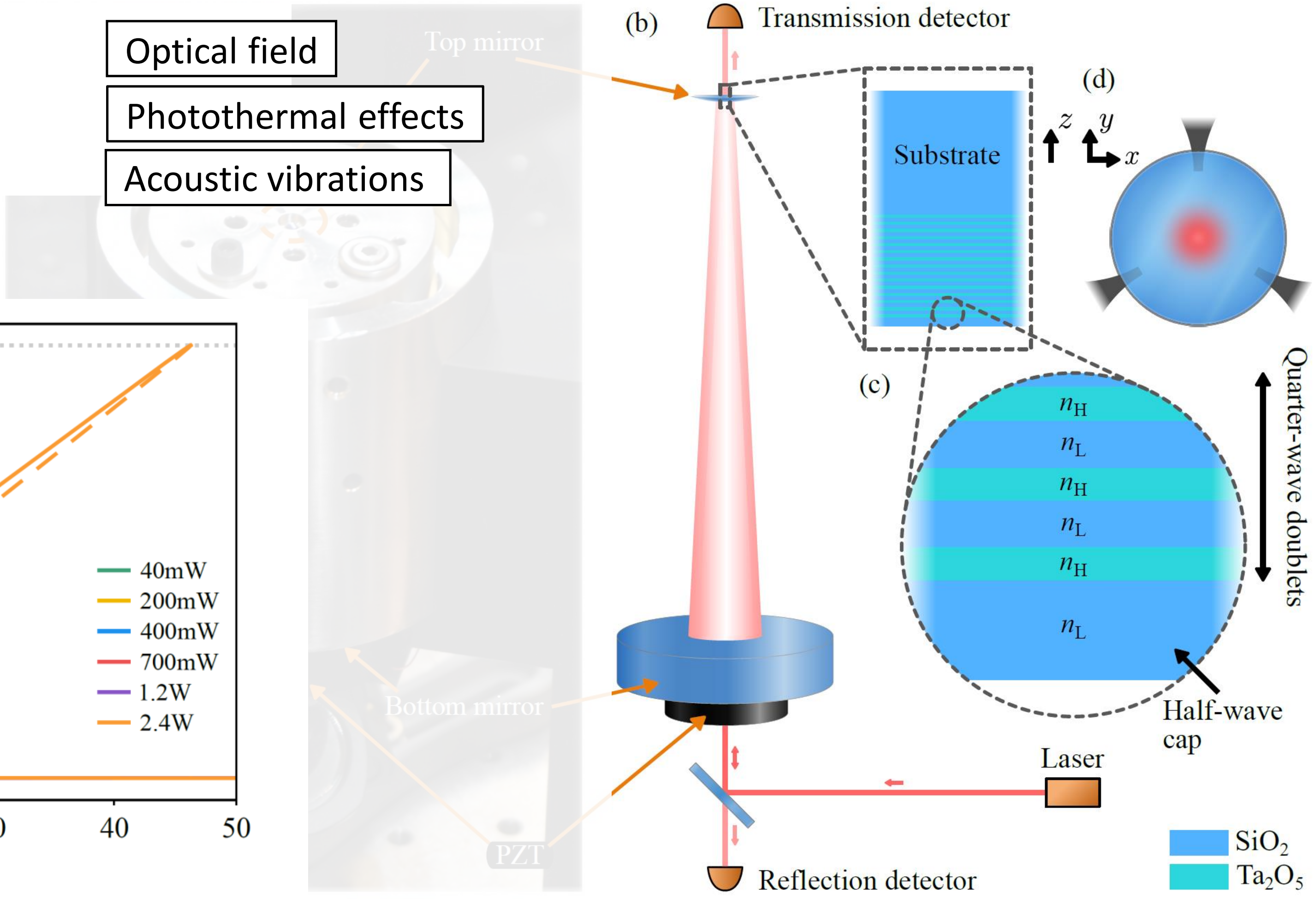
$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{th} + x_{ac}))]\, a + \sqrt{\kappa_{in}} a_{in},$$
$$\dot{x}_{th} = -\gamma_{th}(x_{th} + \beta_{th} P_{opt}(a)),$$
$$\ddot{x}_{ac} = -\gamma_{ac}\dot{x}_{ac} - \omega_{ac}^2 x_{ac} + F_{opt}(a)/m_{ac},$$

Optical field

Photothermal effects

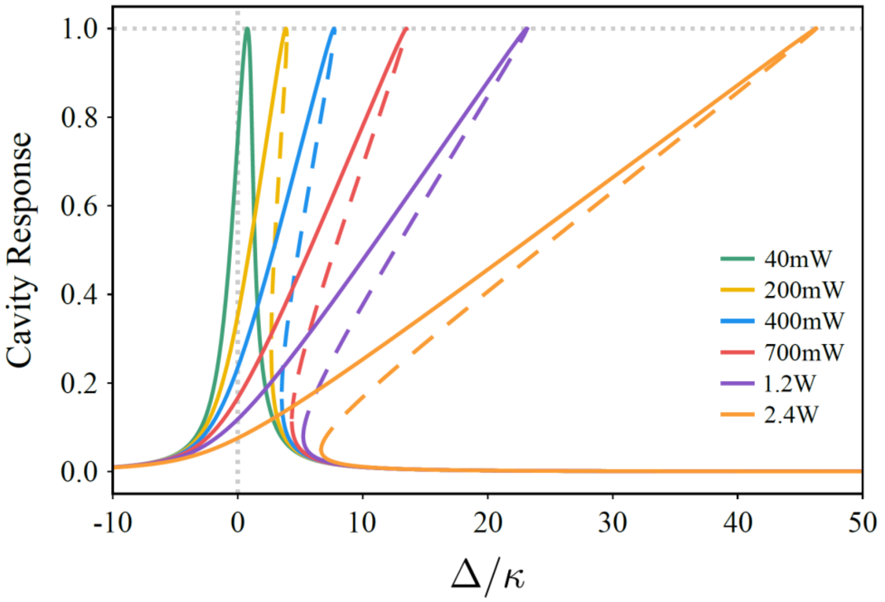
Acoustic vibrations



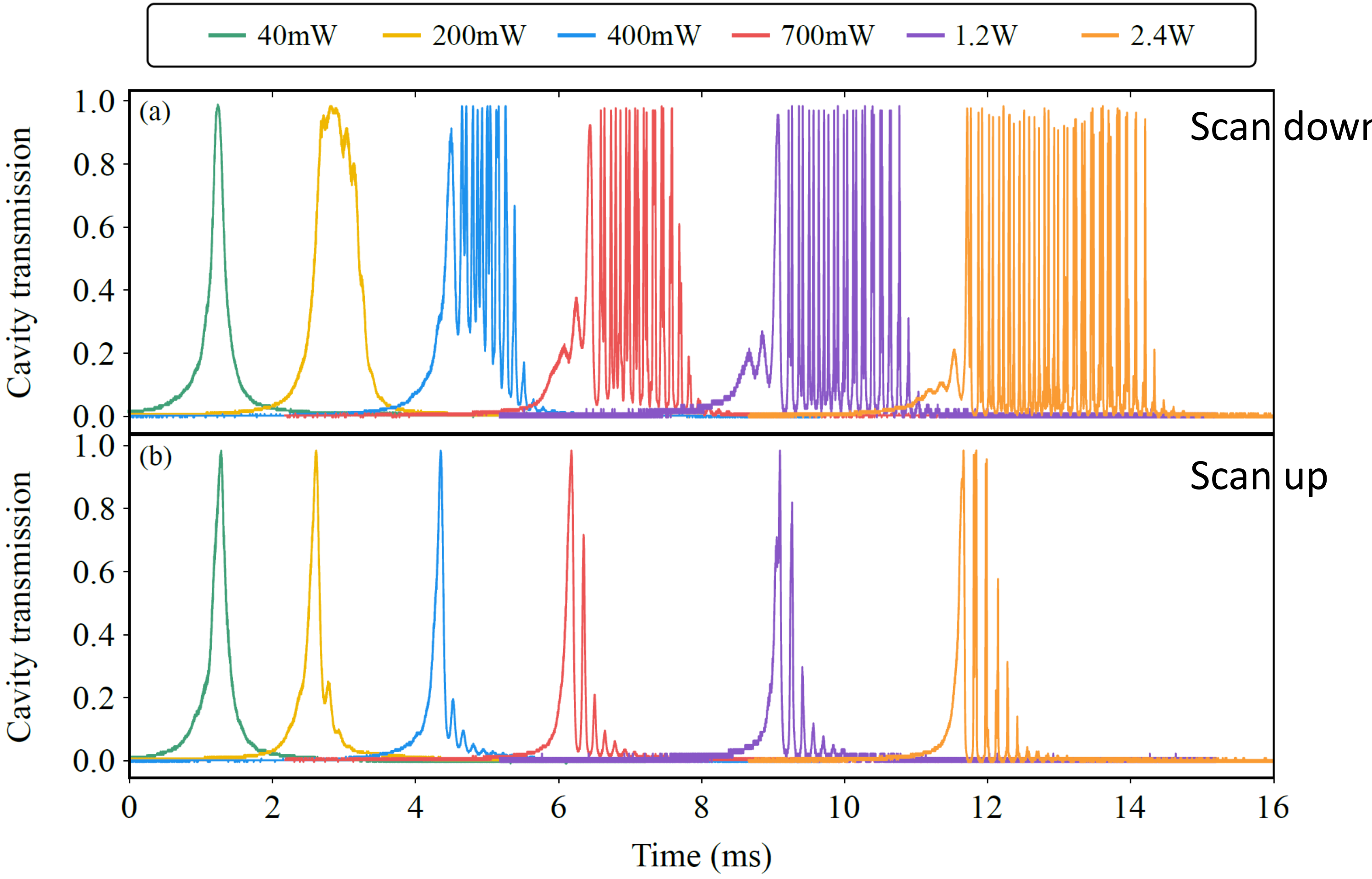


Optomechanical system

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{th} + x_{ac}))]\, a + \sqrt{\kappa_{in}} a_{in},$$
$$\dot{x}_{th} = -\gamma_{th}(x_{th} + \beta_{th} P_{opt}(a)),$$
$$\ddot{x}_{ac} = -\gamma_{ac}\dot{x}_{ac} - \omega_{ac}^2 x_{ac} + F_{opt}(a)/m_{ac},$$

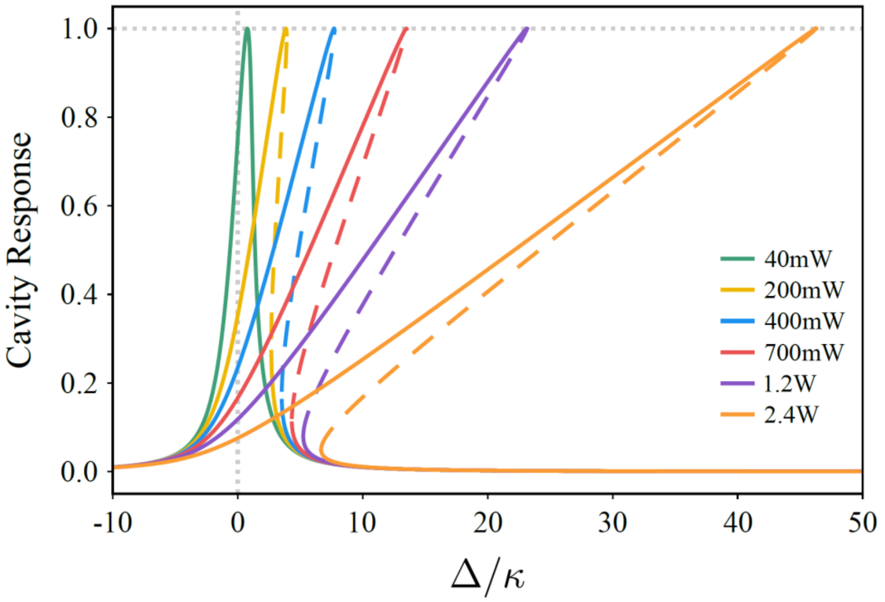


Increasing power

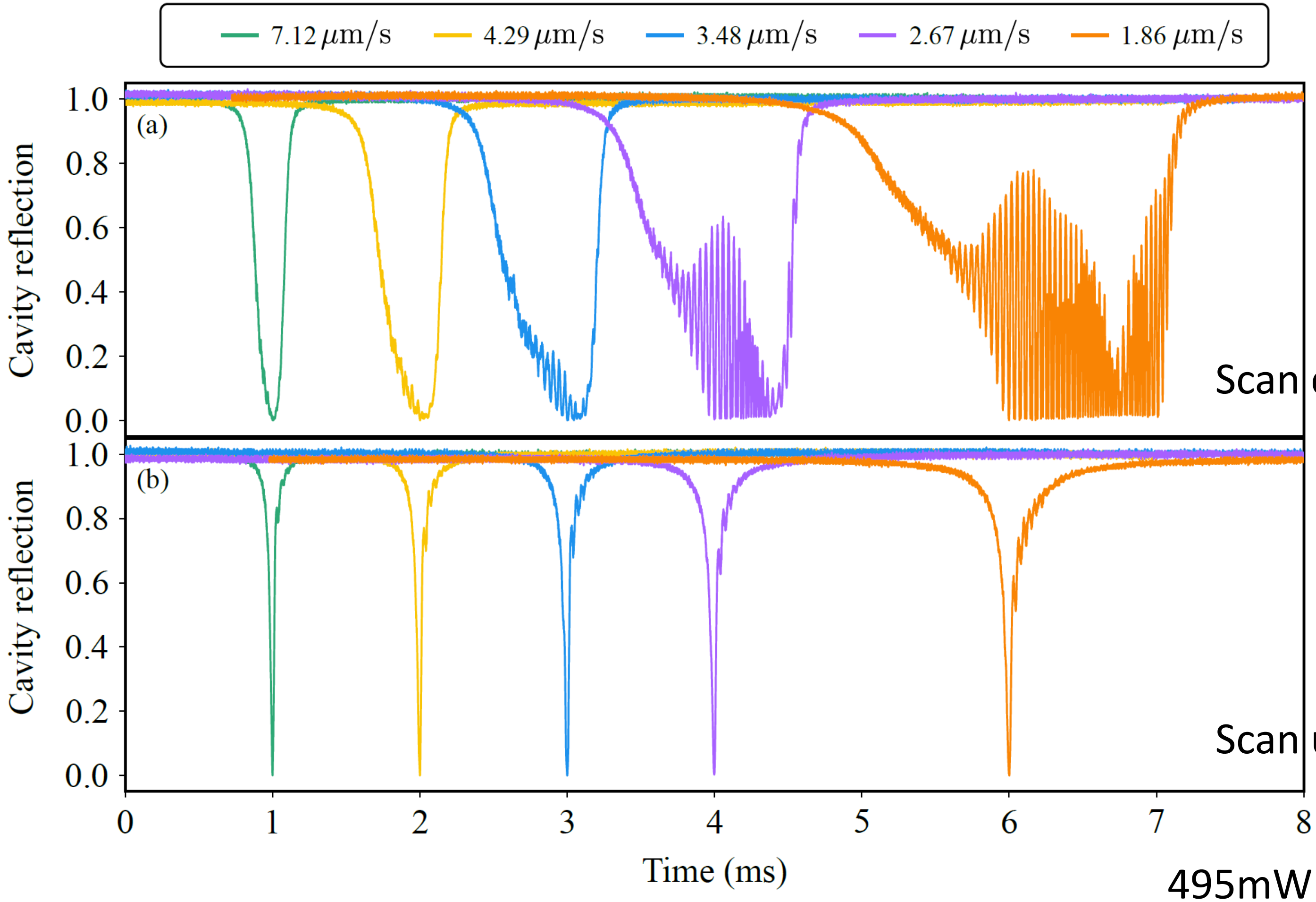


Optomechanical system

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))]\, a + \sqrt{\kappa_{\rm in}} a_{\rm in},$$
$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \beta_{\rm th} P_{\rm opt}(a)),$$
$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac},$$



Decreasing speed



Scan down

Scan up

495mW

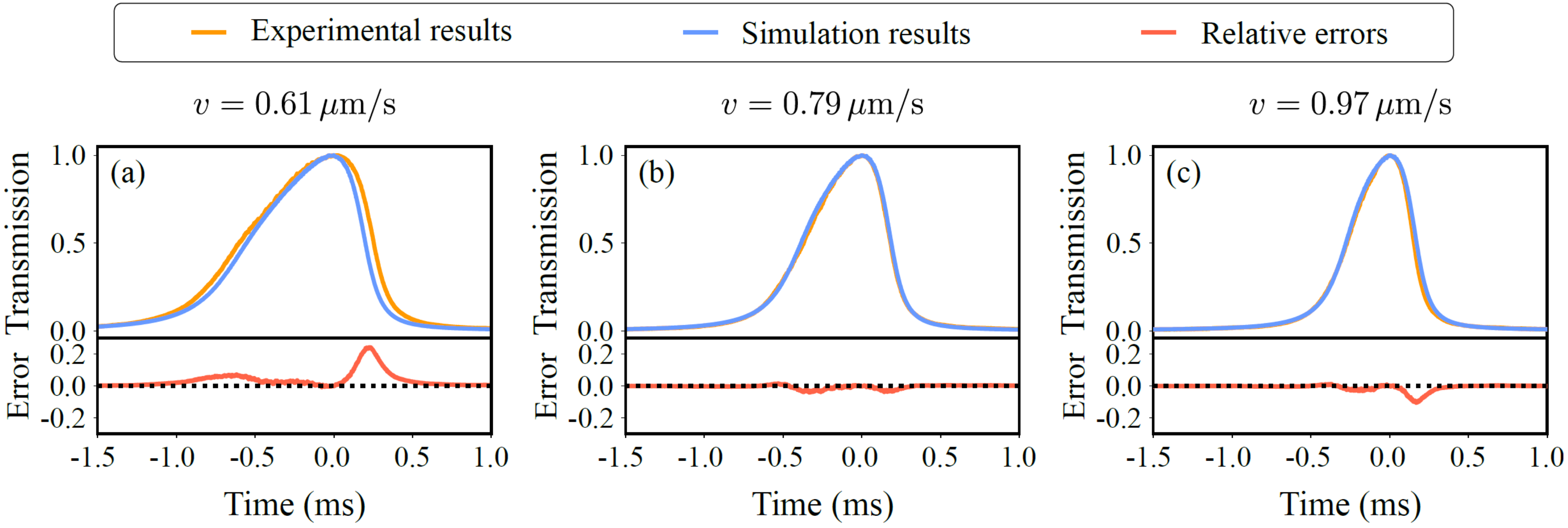
Current model

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\text{th}} + x_{\text{ac}}))]\, a + \sqrt{\kappa_{\text{in}}} a_{\text{in}}, \quad (3.1)$$

$$\dot{x}_{\text{th}} = -\gamma_{\text{th}}(x_{\text{th}} + \beta_{\text{th}} P_{\text{opt}}(a)), \quad (3.2)$$

$$\ddot{x}_{\text{ac}} = -\gamma_{\text{ac}}\dot{x}_{\text{ac}} - \omega_{\text{ac}}^2 x_{\text{ac}} + F_{\text{opt}}(a)/m_{\text{ac}}, \quad (3.3)$$

93mW



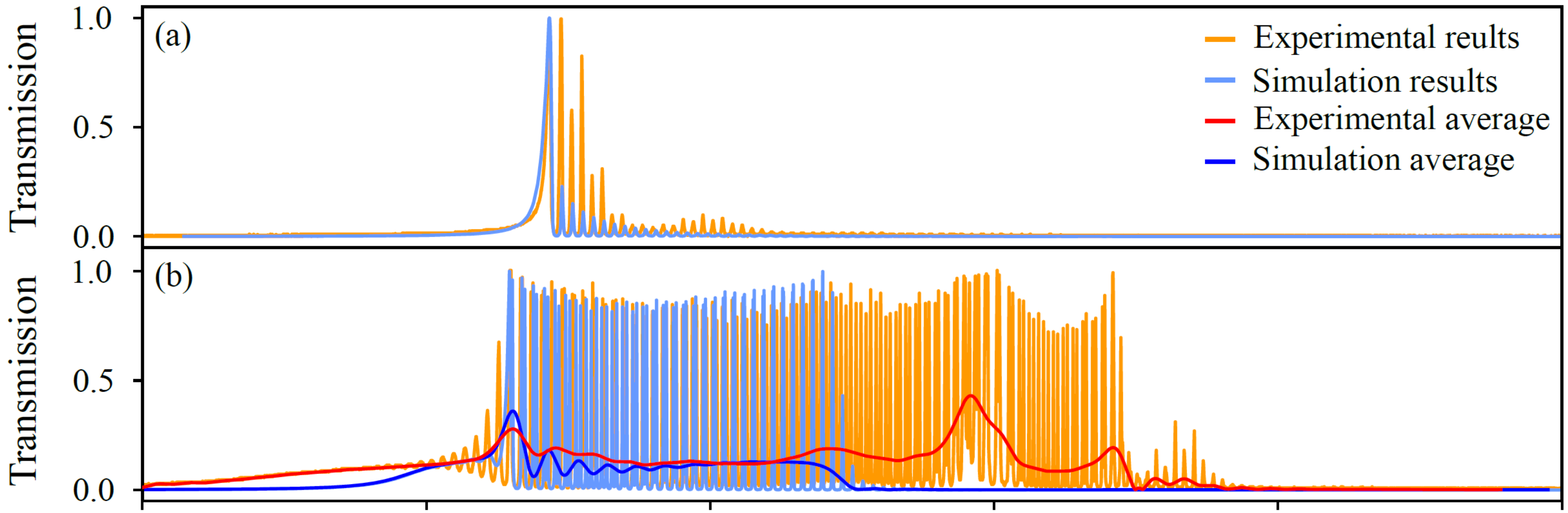
Current model

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))]\, a + \sqrt{\kappa_{\rm in}} a_{\rm in}, \quad (3.1)$$

$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \beta_{\rm th} P_{\rm opt}(a)), \quad (3.2)$$

$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac}, \quad (3.3)$$

2.75W



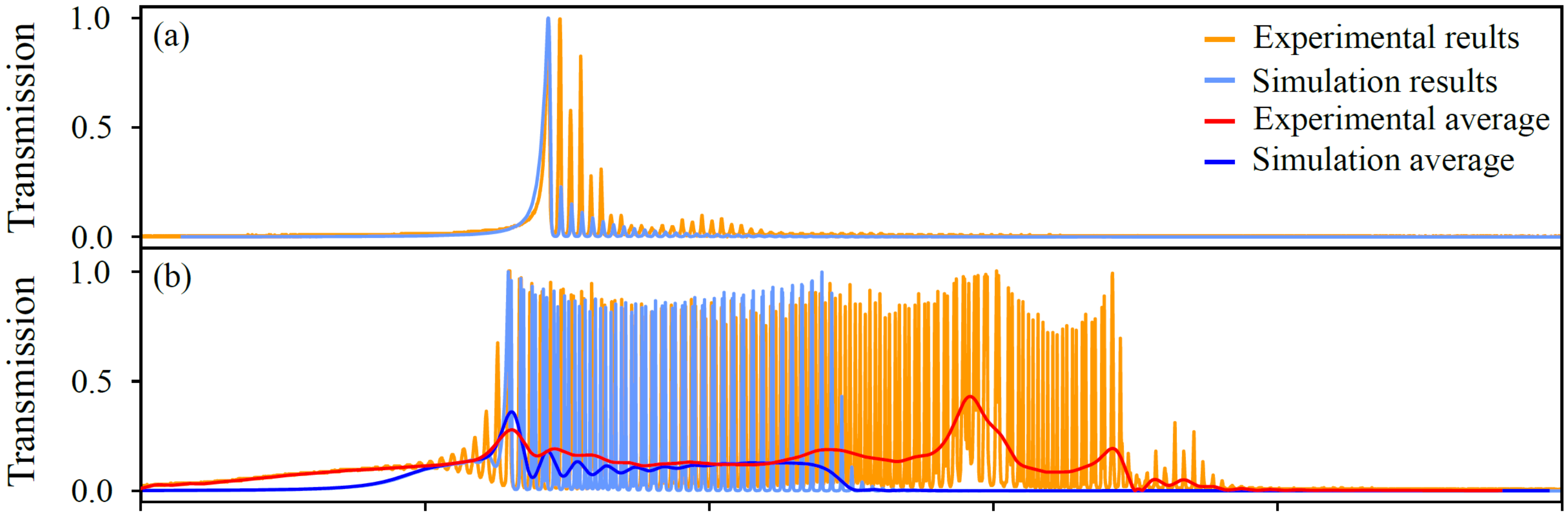
Current model

Australian National University

?

1. Stabilization of the cavity

2. A better model



Photothermal cancellation

Australian National University

1. Optomechanics

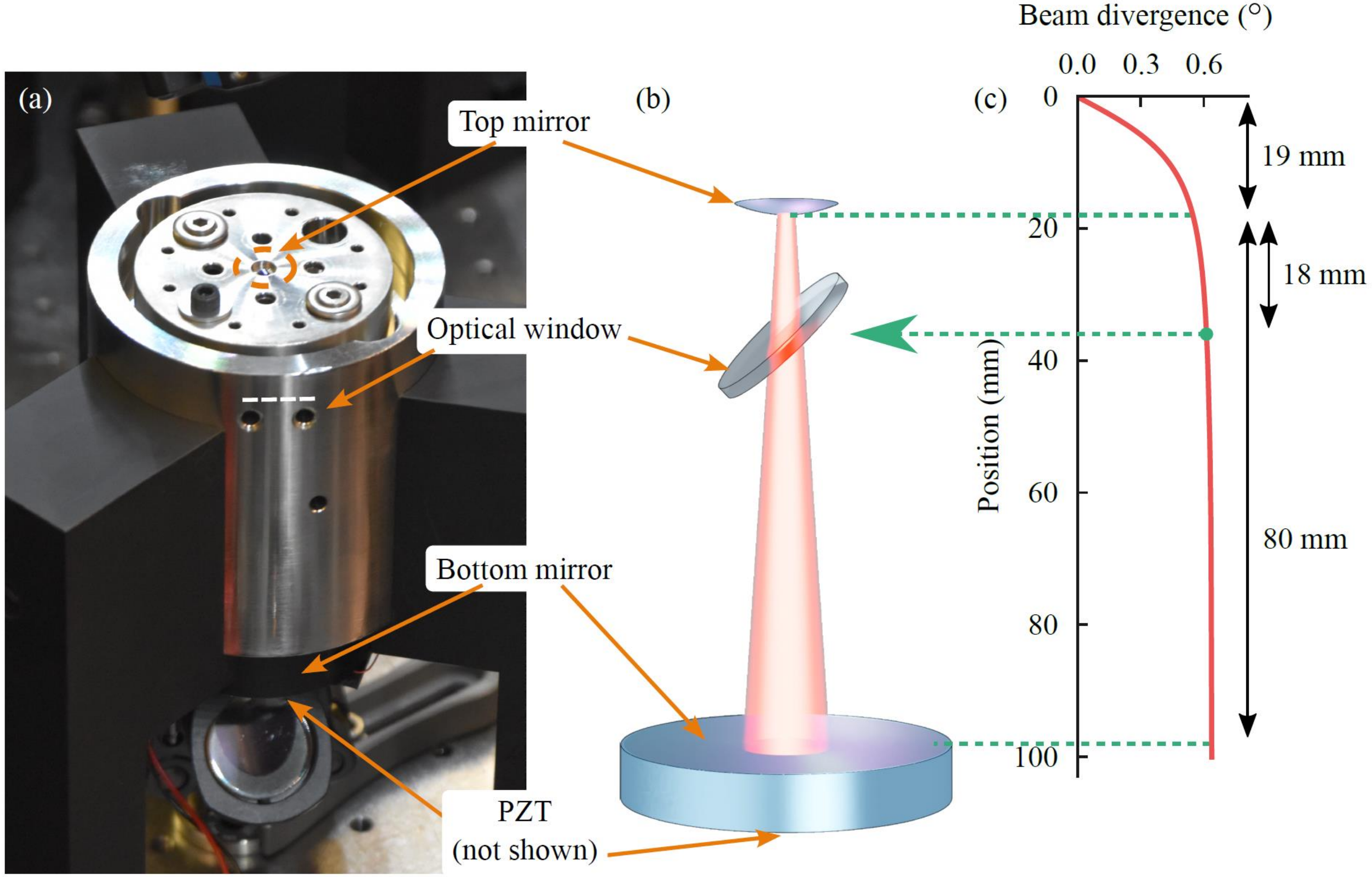
2. Optical-levitation System and Current Model

3. Photothermal Cancellation

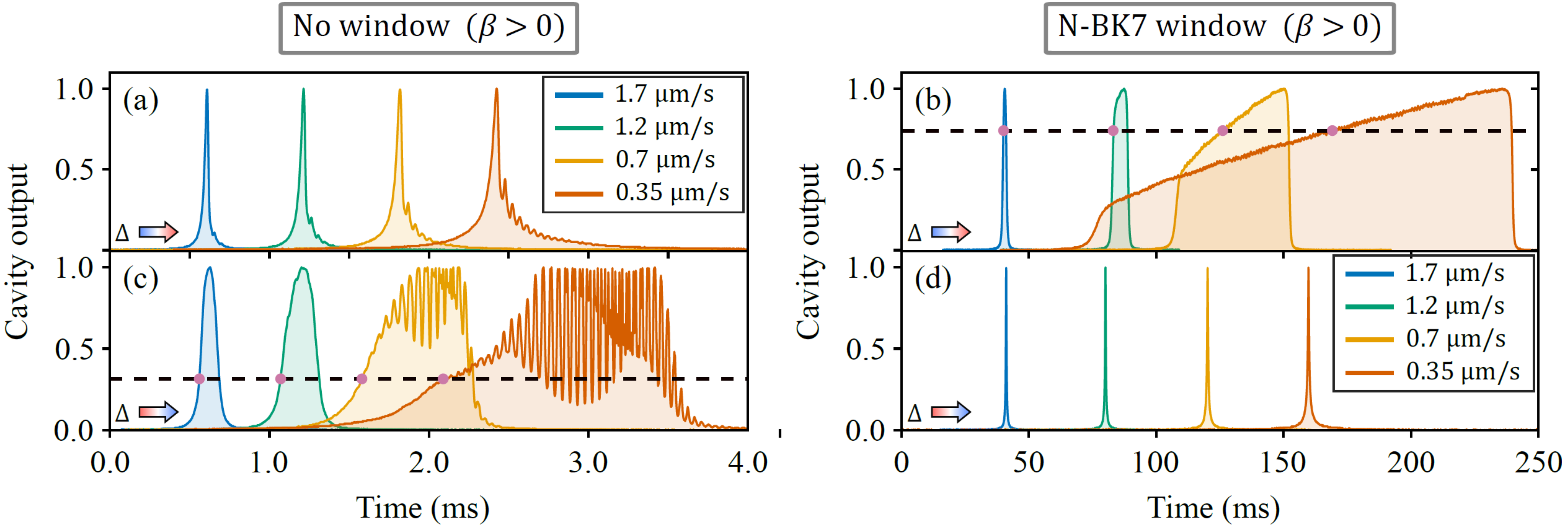
4. Model with multiple photothermal effects

Photothermal cancellation

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{th} + x_{ac}))]\, a + \sqrt{\kappa_{in}} a_{in},$$
$$\dot{x}_{th} = -\gamma_{th}(x_{th} + \boxed{\beta_{th}} P_{opt}(a)),$$
$$\ddot{x}_{ac} = -\gamma_{ac}\dot{x}_{ac} - \omega_{ac}^2 x_{ac} + F_{opt}(a)/m_{ac},$$



Photothermal cancellation



Photothermal cancellation

Australian National University

Table 4.1: Parameters of the cavity with different optical windows.

	Bare	Sapphire	N-BK7 ×1	N-BK7 ×2	N-BK7 ×4	N-BK7 thick
Refractive index	—	1.77	1.52	1.52	1.52	1.52
Thickness (mm)	—	3.0	0.22	0.44	0.88	1.0
Photothermal coefficient, $\sigma_{\text{th}}/2\pi$ (Hz pm W^{-1})	3750(650)	2870(350)	2120(740)	960(230)	N/A	-22380(670)
Photothermal relaxation rate, $\gamma_{\text{th}}/2\pi$ (Hz)	426(145)	279(10)	380(115)	151(51)	N/A	4.39(13)
Photothermal susceptivity, β_{th} (pm W^{-1})	9.3(19)	10.5(13)	7.0(6)	6.6(15)	N/A	-5100(20)
Cavity finesse	2850	2240	2350	2070	2030	650
Cavity linewidth, κ (MHz)	0.33	0.42	0.40	0.45	0.46	1.44

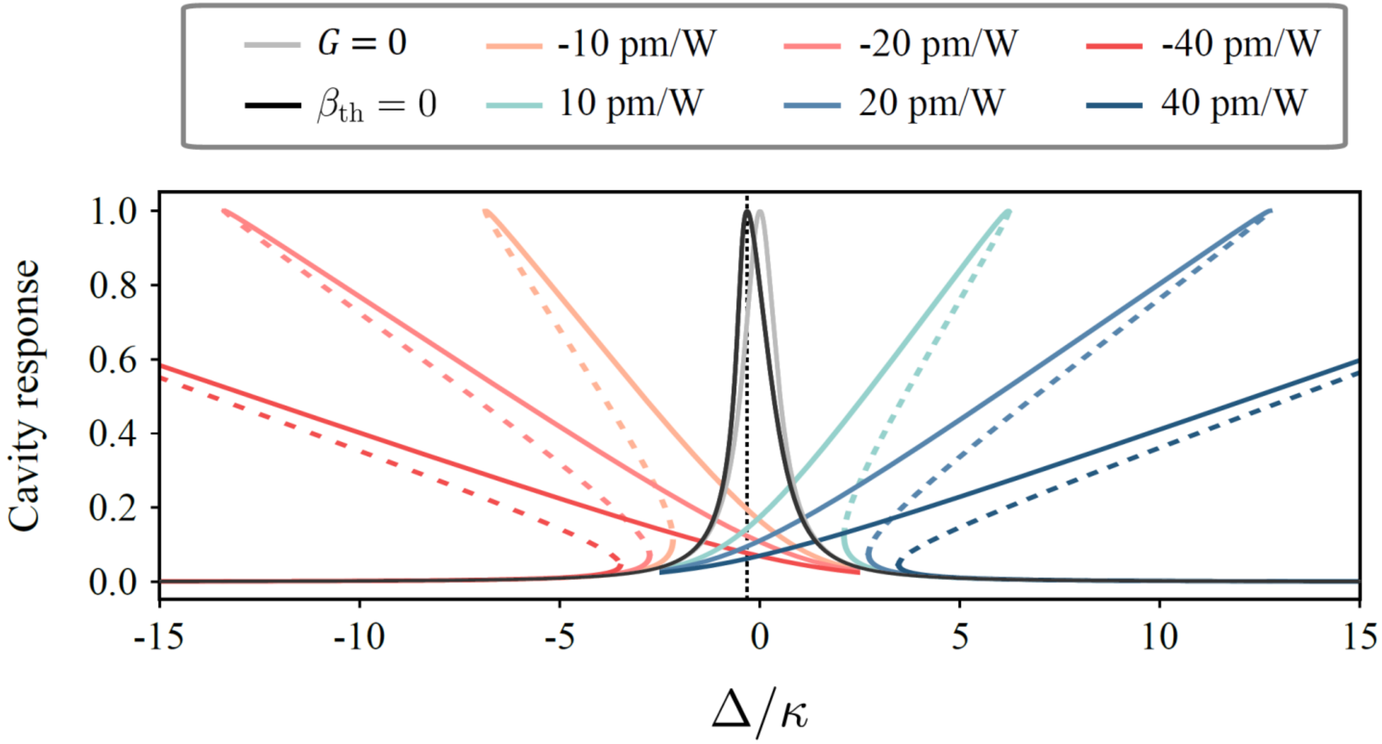
Photothermal cancellation

Australian National University

$$\dot{a} = \left[-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))\right] a + \sqrt{\kappa_{\rm in}} a_{\rm in}, \quad (3.1)$$

$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \boxed{\beta_{\rm th}} P_{\rm opt}(a)), \quad (3.2)$$

$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac}, \quad (3.3)$$

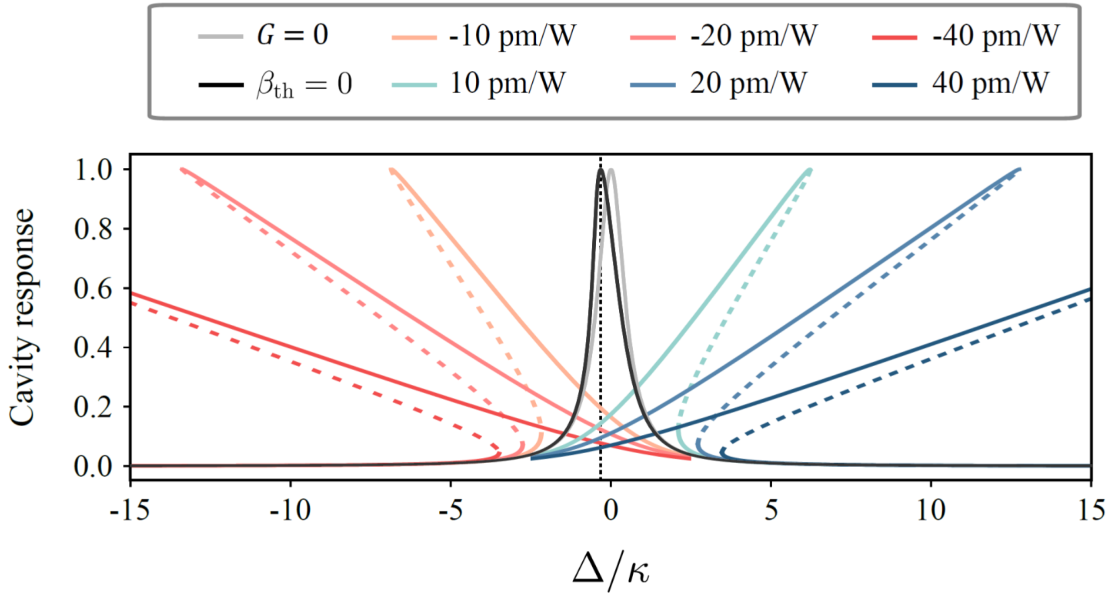


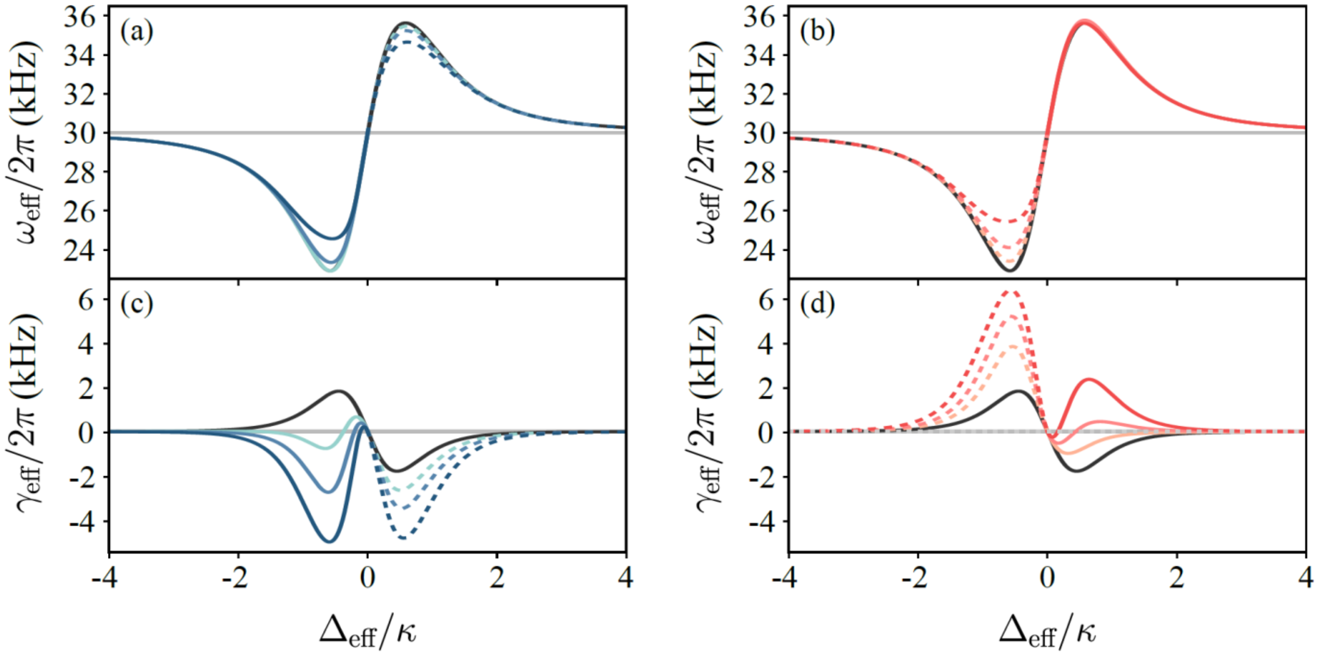
Photothermal cancellation

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))]\, a + \sqrt{\kappa_{\rm in}} a_{\rm in}, \quad (3.1)$$

$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \beta_{\rm th} P_{\rm opt}(a)), \quad (3.2)$$

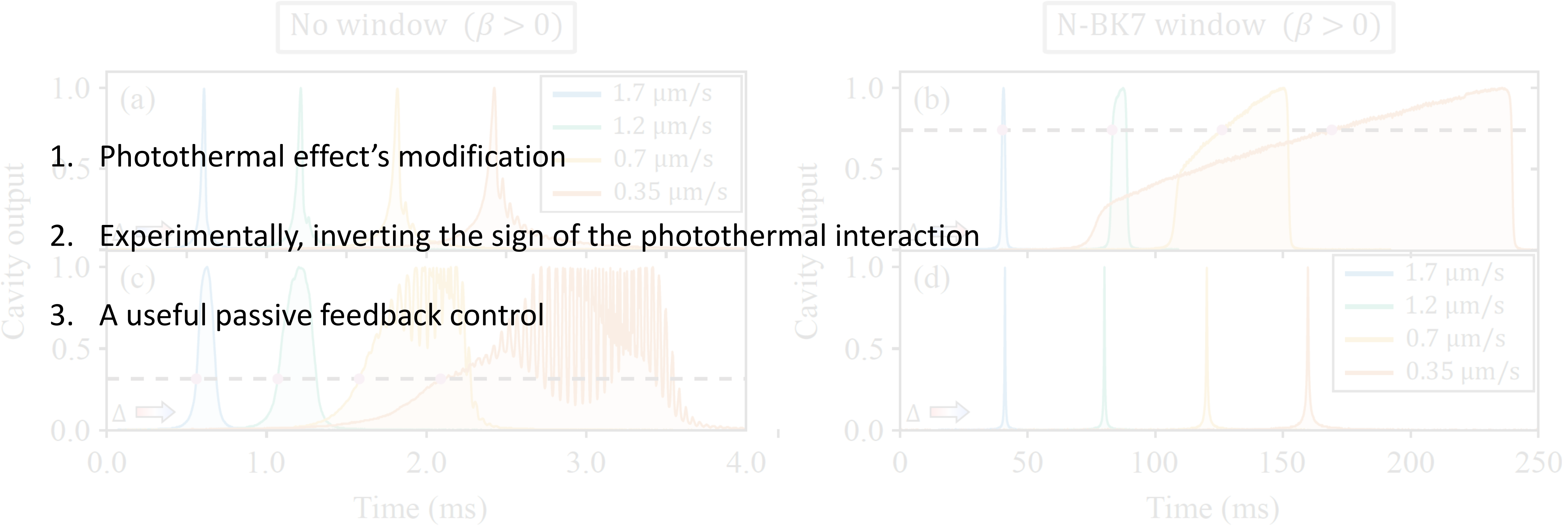
$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac}, \quad (3.3)$$





Photothermal cancellation

Australian National University



1. Photothermal effect’s modification
2. Experimentally, inverting the sign of the photothermal interaction
3. A useful passive feedback control

Photothermal effects

Australian National University

1. Optomechanics

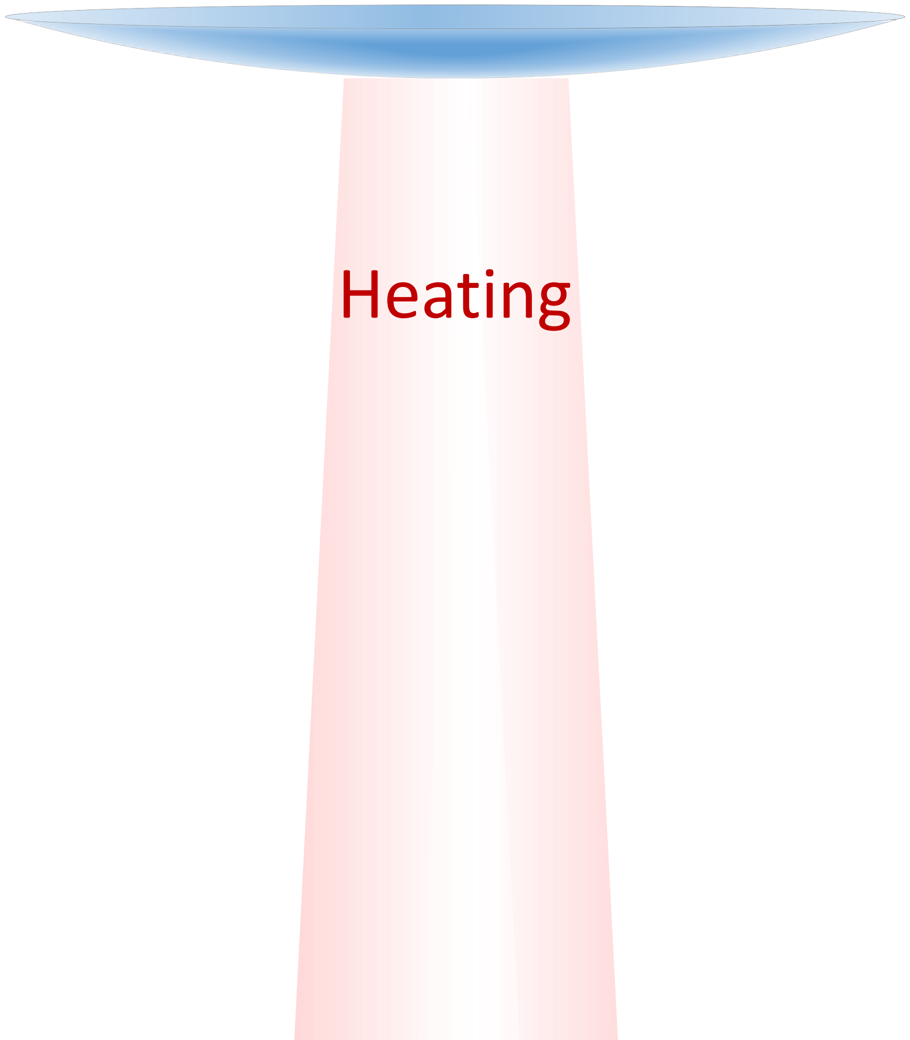
2. Optical-levitation System and Current Model

3. Photothermal Cancellation

4. Model with multiple photothermal effects

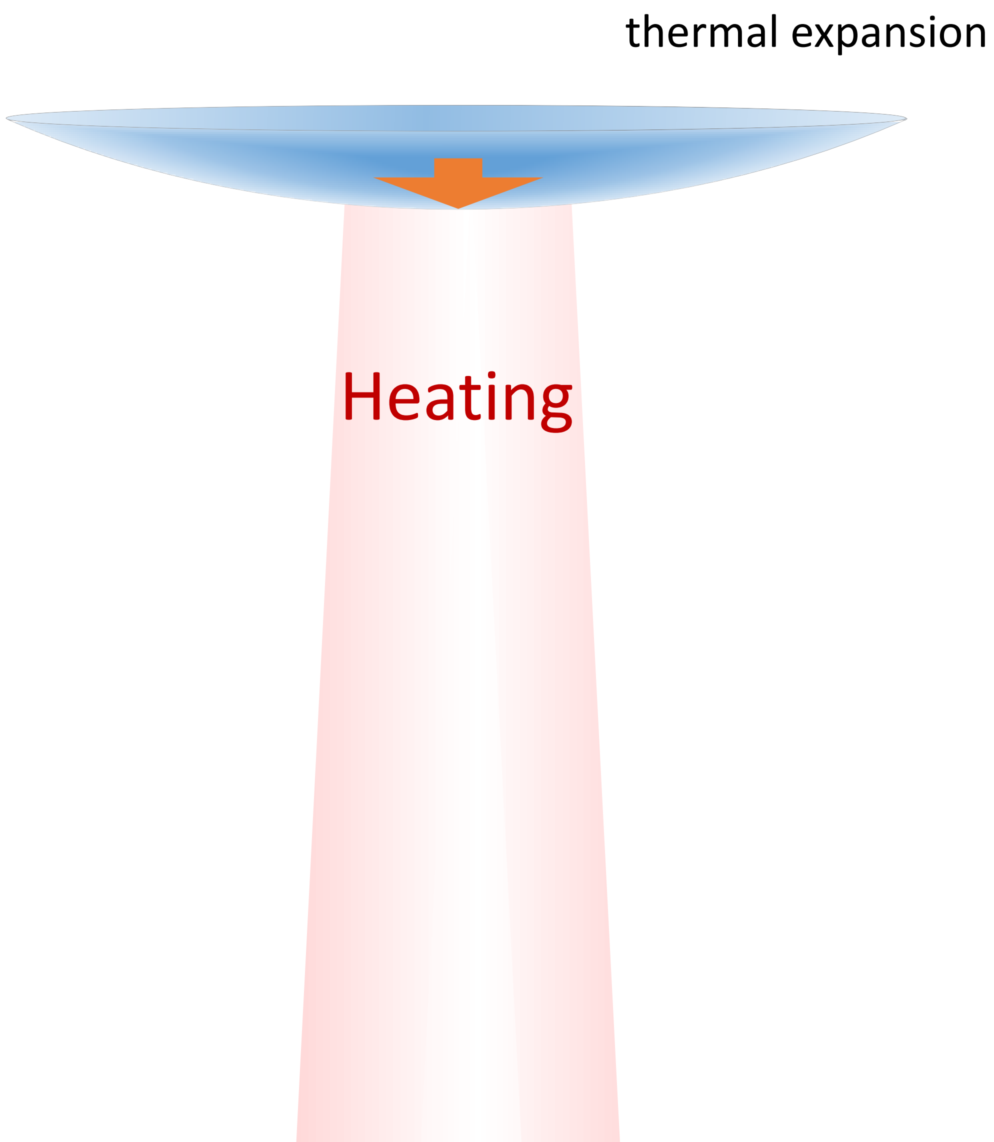
Photothermal effects

Australian National University



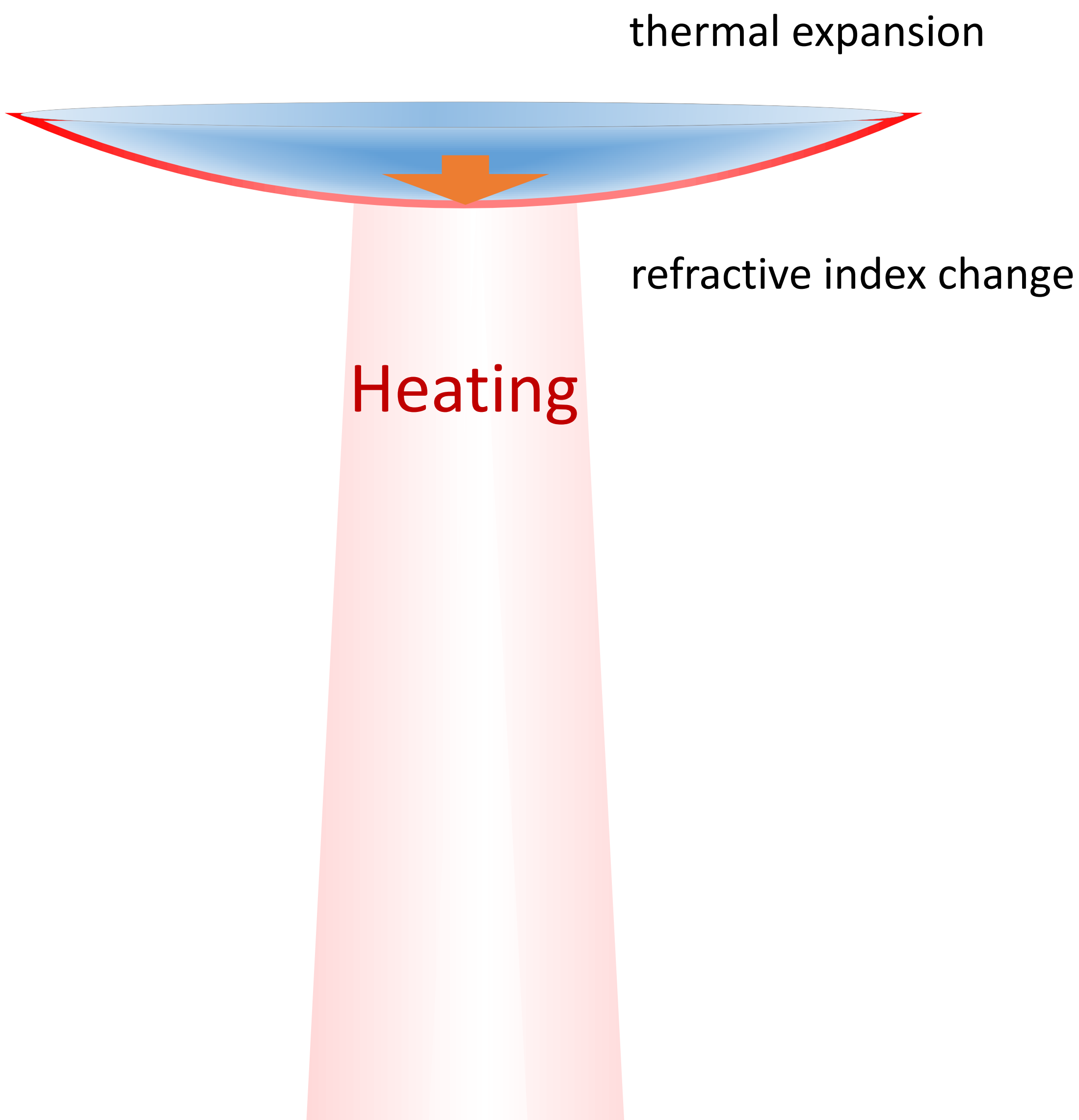
[5] Ghosh, G. (1998). Academic Press.
[6] Borgogno, J. P., et al. (1984). *Applied optics*, *23*(20), 3567-3570.
[7] Wiechmann, S., & Müller, J. (2009). *Thin solid films*, *517*(24), 6847-6849.

Photothermal effects



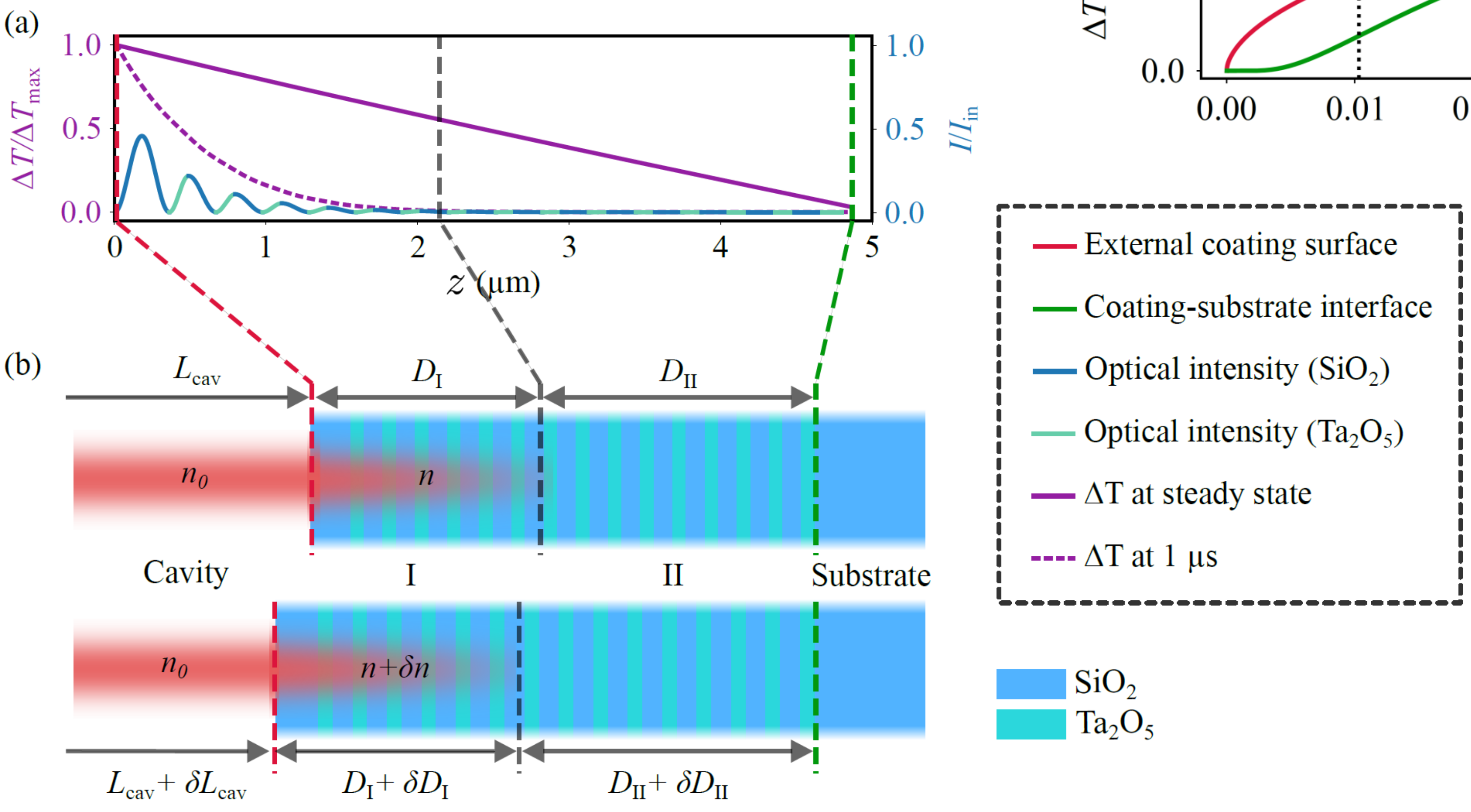
[5] Ghosh, G. (1998). Academic Press.
[6] Borgogno, J. P., et al. (1984). *Applied optics*, *23*(20), 3567-3570.
[7] Wiechmann, S., & Müller, J. (2009). *Thin solid films*, *517*(24), 6847-6849.

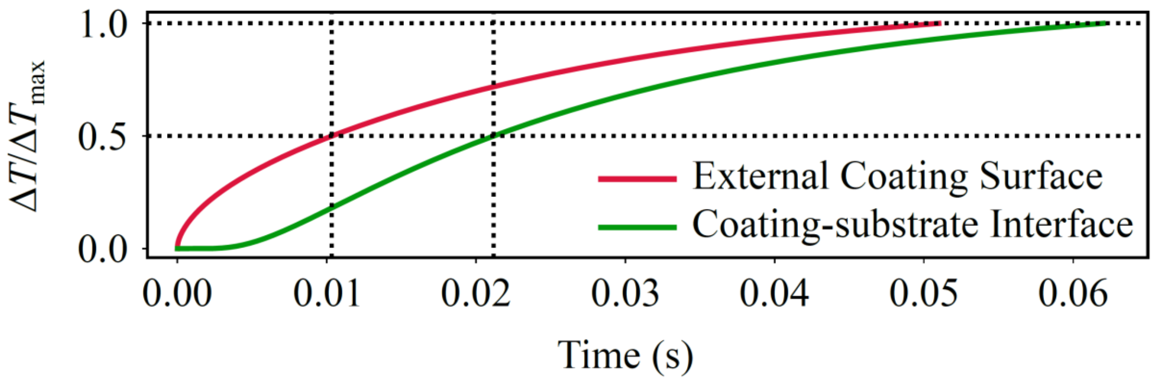
Photothermal effects



[5] Ghosh, G. (1998). Academic Press.
[6] Borgogno, J. P., et al. (1984). *Applied optics*, *23*(20), 3567-3570.
[7] Wiechmann, S., & Müller, J. (2009). *Thin solid films*, *517*(24), 6847-6849.

Photothermal effects





Refined model

Australian National University

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))]\, a + \sqrt{\kappa_{\rm in}} a_{\rm in},$$

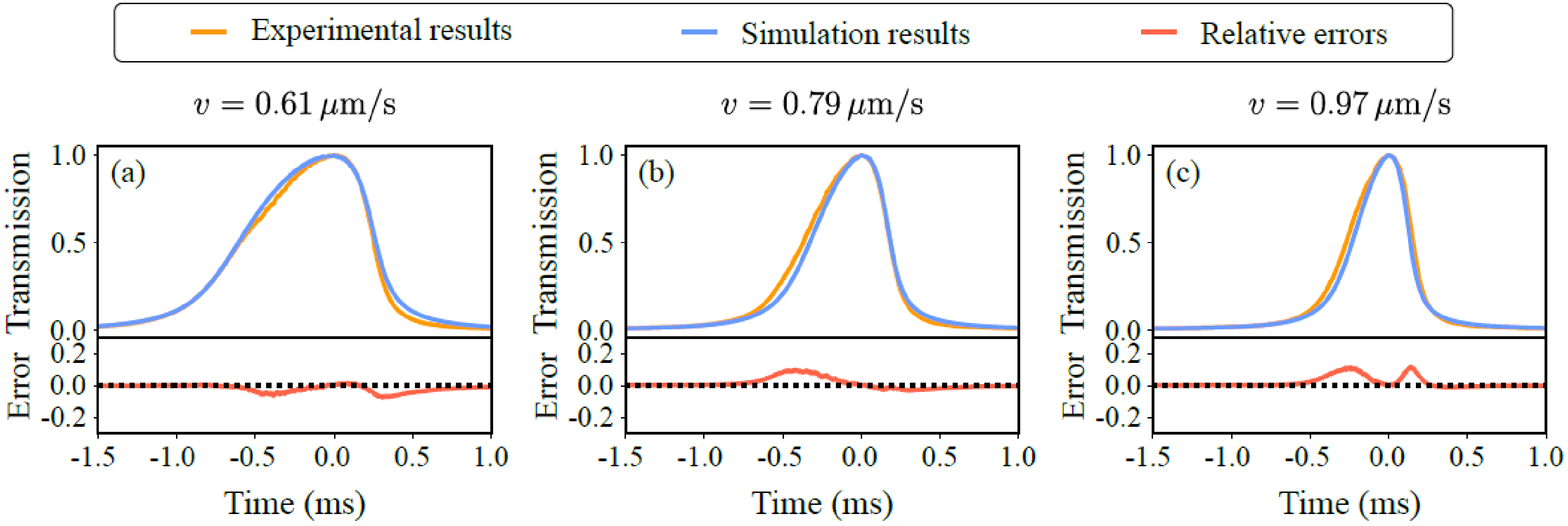
$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \beta_{\rm th} P_{\rm opt}(a)),$$

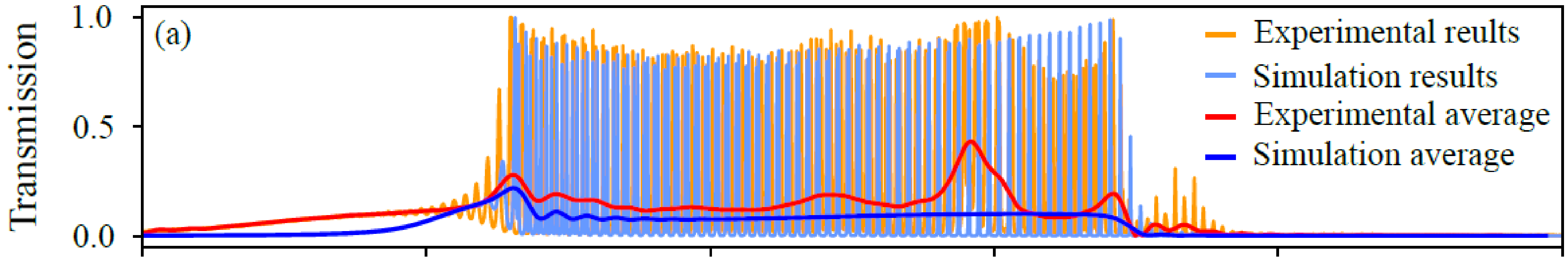
$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac},$$

Photothermal expansion $$\dot{x}_{\rm ex} = -\gamma_{\rm ex}(x_{\rm ex} + \beta_{\rm ex} P_{\rm opt}(a)),$$

Thermo-optic effect $$\dot{x}_{\rm re} = -\gamma_{\rm re}(x_{\rm re} - \beta_{\rm re} P_{\rm opt}(a)),$$

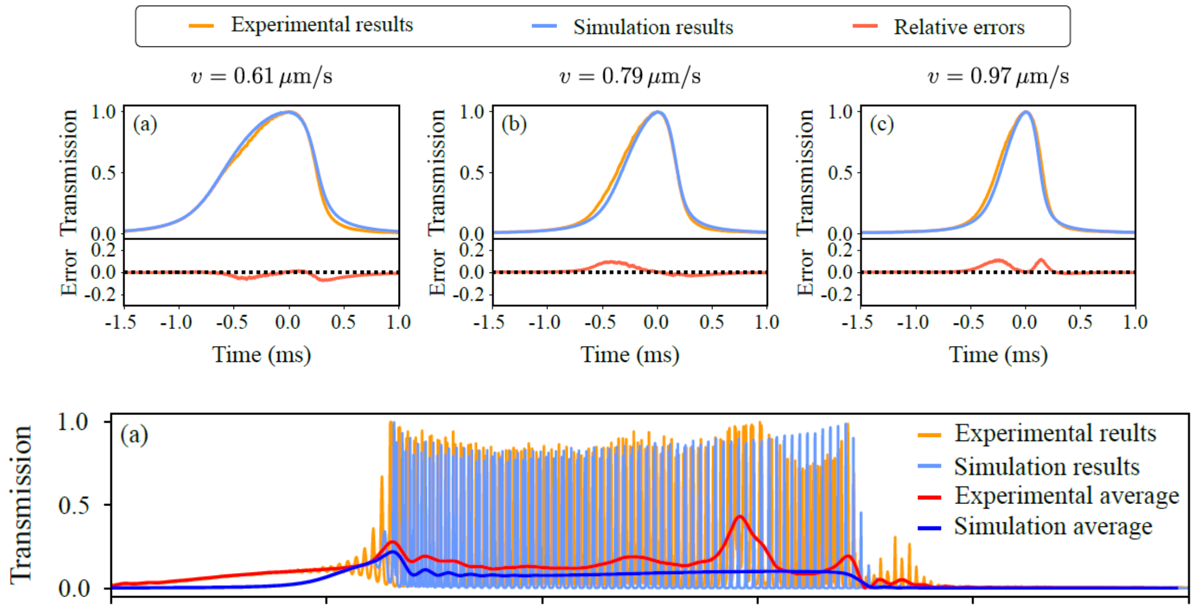
Refined model



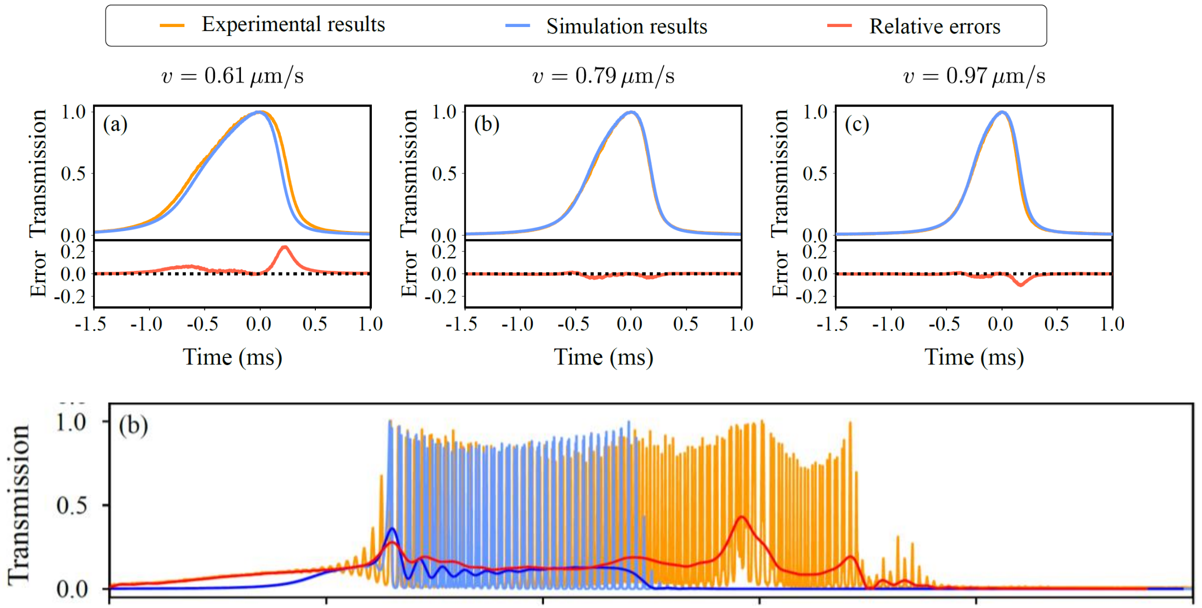


Refined model

Refined model



Original model



Nonlinearity of photothermal effects

Australian National University

$$\dot{a} = [-\kappa/2 + i(\Delta + G(x_{\rm th} + x_{\rm ac}))]\, a + \sqrt{\kappa_{\rm in}} a_{\rm in},$$

$$\dot{x}_{\rm th} = -\gamma_{\rm th}(x_{\rm th} + \beta_{\rm th} P_{\rm opt}(a)),$$

$$\ddot{x}_{\rm ac} = -\gamma_{\rm ac}\dot{x}_{\rm ac} - \omega_{\rm ac}^2 x_{\rm ac} + F_{\rm opt}(a)/m_{\rm ac},$$

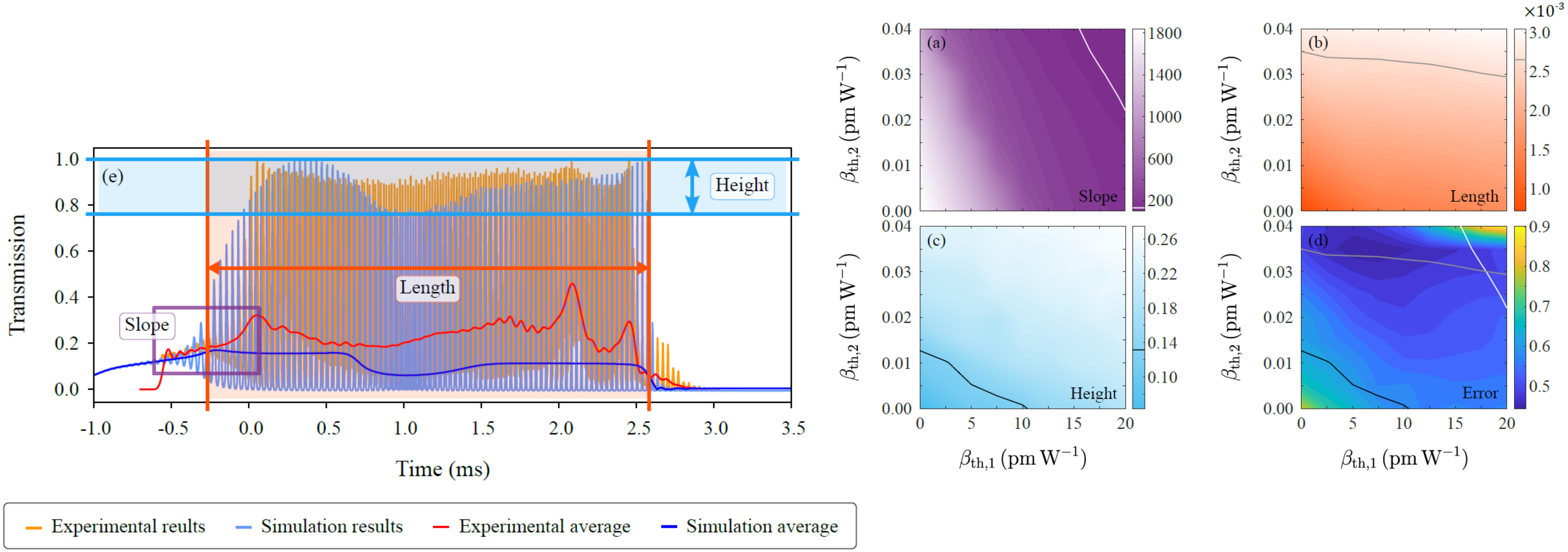
$$\dot{x}_{th} = -\gamma_{th}[x_{th} + \beta(P_{opt})]$$

photothermal response coefficient to optical power:

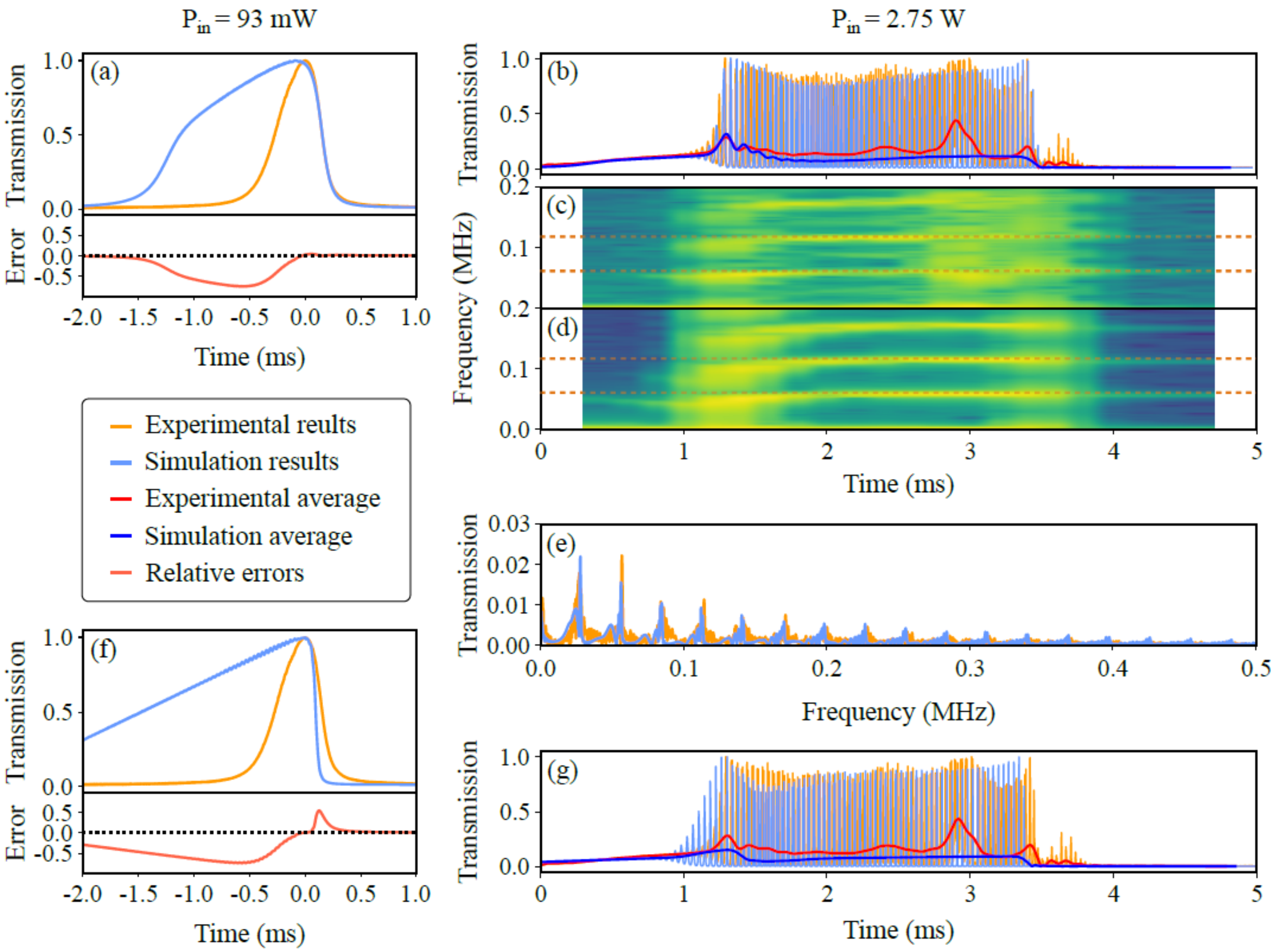
Linear: $\beta(P_{opt}) = \beta_1 P_{opt} \rightarrow \dot{x}_{th} = -\gamma_{th}[x_{th} + \beta_1 P_{opt}]$

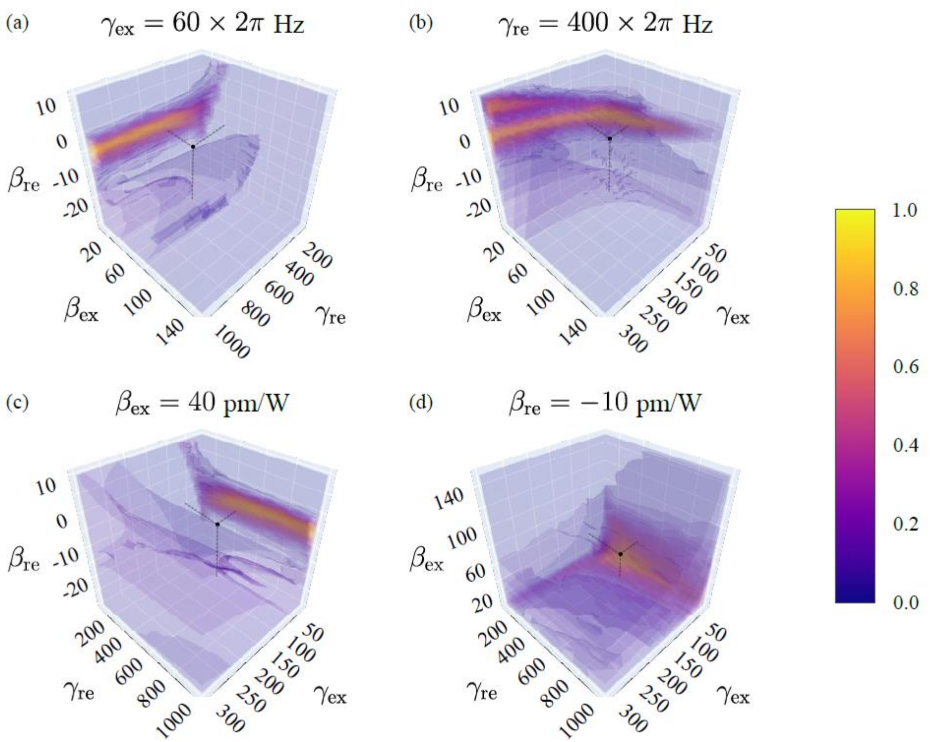
Nonlinear: $\beta(P_{opt}) = \beta_1 P_{opt} + \beta_2 P_{opt}^2 \rightarrow \dot{x}_{th} = -\gamma_{th}[x_{th} + \beta_1 P_{opt} + \beta_2 P_{opt}^2]$

Nonlinearity of photothermal effects



More discussion





Photothermal effects

1. Thermal conduction of the coating
2. Two photothermal effects are necessary for a more precise simulation
3. Better model? More investigation in other effects

Future work

Australian National University

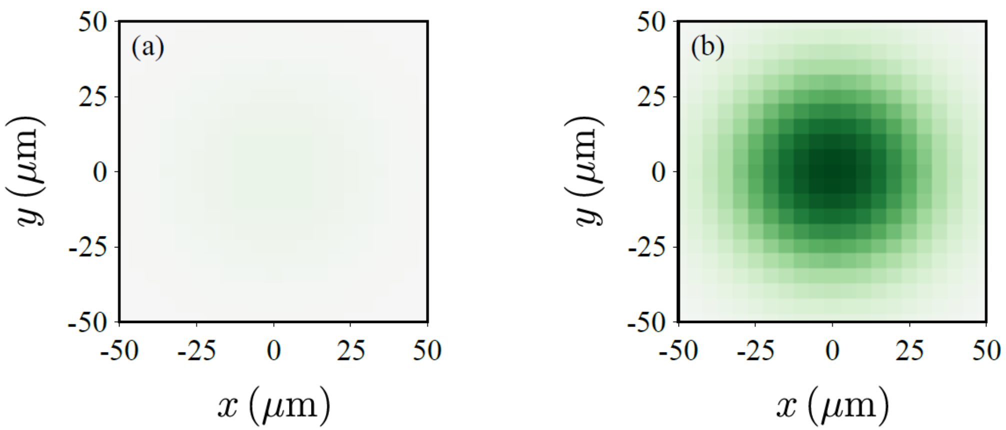
1. Nonlinearity of the photothermal effects
    1) a better model
    2) experimental observation

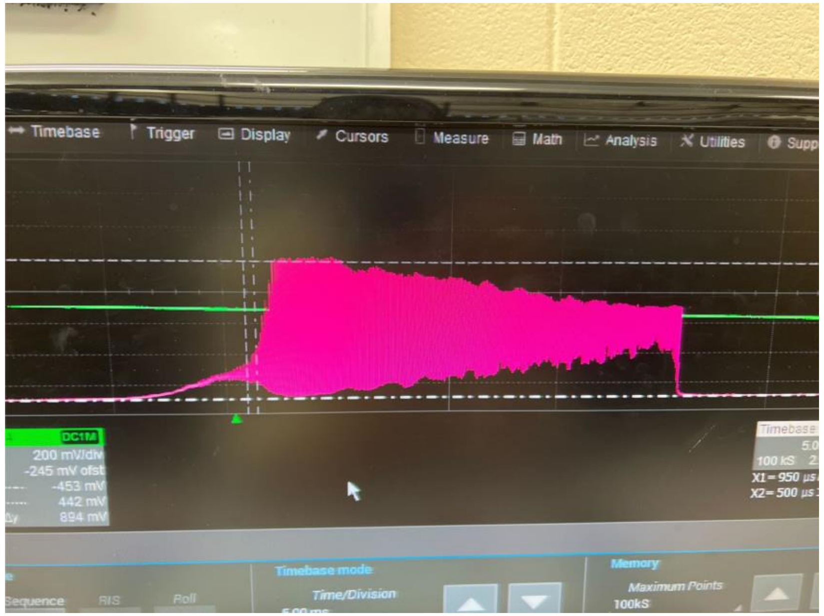
2. Characterize the optical spring from the experiments

3. Cancellation of photothermal effects experimentally

4. Other ways to stabilize the cavity

5. Other proposals for optical levitation





Conclusion

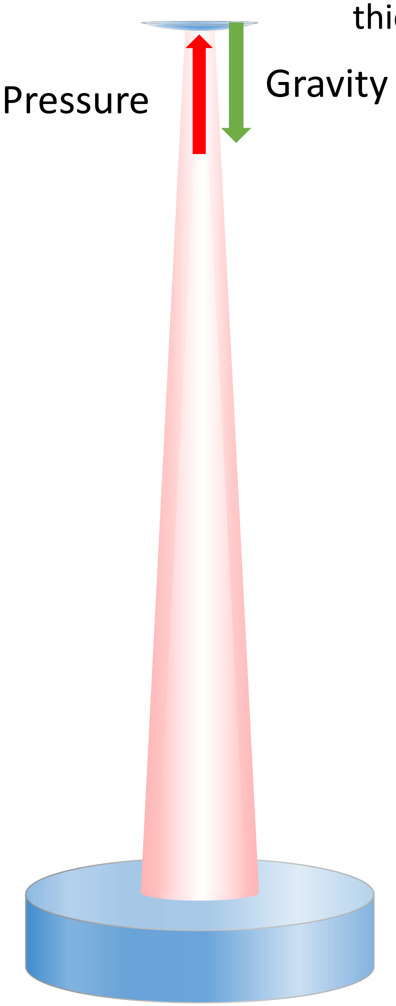
Australian National University

1. Optomechanics

2. Optical-levitation System and Current Model

3. Photothermal Cancellation

4. Model with multiple photothermal effects



References

[1] Aspelmeyer, M., et al. (2014). Reviews of Modern Physics, 86(4), 1391.
[2] Delić, U., et al. (2020). Science, 367(6480), 892-895.
[3] Konthasinghe, K., et al. (2017). Physical Review A, 95(1), 013826.
[4] Ma, J., et al. (2020). Communications Physics, 3(1), 1-10
[5] Ghosh, G. (1998). Academic Press.
[6] Borgogno, J. P., et al. (1984). Applied optics, 23(20), 3567-3570.
[7] Wiechmann, S., & Müller, J. (2009). Thin solid films, 517(24), 6847-6849.
[8] Ashkin, A. (1970). Physical review letters, 24(4), 156

Conclusion

Australian National University

1. Optomechanics

2. Optical-levitation System and Current Model

3. Photothermal Cancellation

4. Model with multiple photothermal effects

Thank you

References

[1] Aspelmeyer, M., et al. (2014). Reviews of Modern Physics, 86(4), 1391.
[2] Delić, U., et al. (2020). Science, 367(6480), 892-895.
[3] Konthasinghe, K., et al. (2017). Physical Review A, 95(1), 013826.
[4] Ma, J., et al. (2020). Communications Physics, 3(1), 1-10
[5] Ghosh, G. (1998). Academic Press.
[6] Borgogno, J. P., et al. (1984). Applied optics, 23(20), 3567-3570.
[7] Wiechmann, S., & Müller, J. (2009). Thin solid films, 517(24), 6847-6849.

Optomechanical system

$$
\begin{aligned}
\dot{a} &= \left[-\kappa/2 + i(\Delta + G(x_{\text{lev}} + x_{\text{th}} + x_{\text{ac}}))\right] a + \sqrt{\kappa_{\text{in}}} a_{\text{in}}, \\
\dot{x}_{\text{th}} &= -\gamma_{\text{th}}(x_{\text{th}} + \beta_{\text{th}} P_{\text{opt}}(a)), \\
\ddot{x}_{\text{ac}} &= -\gamma_{\text{ac}}\dot{x}_{\text{ac}} - \omega_{\text{ac}}^2 x_{\text{ac}} + F_{\text{opt}}(a)/m_{\text{ac}}, \\
\ddot{x}_{\text{lev}} &= \begin{cases} -\gamma_{\text{lev}}\dot{x}_{\text{lev}} & F_{\text{opt}} \leq F_{\text{g}}, \\ -\gamma_{\text{lev}}\dot{x}_{\text{lev}} + (F_{\text{opt}}(a) - F_{\text{g}})/m & F_{\text{opt}} > F_{\text{g}}, \end{cases}
\end{aligned}
$$

Optical field

Photothermal effects

Acoustic vibrations

Optical lift