香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Direct Measurement of Optical Force Induced by Near-Field Plasmonic Cavity Using Dynamic Mode AFM

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This work was supported by Grant No. AoE/P-02/12. No. HKUST 605013.

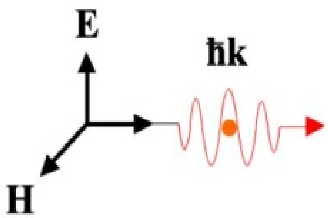
Outline

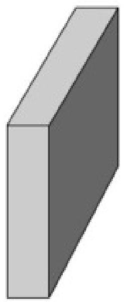
- **Introduction**
- **Experiment**
- **Results**
- **Conclusion**

Guan, D. et al. Sci. Rep. ***5****, 16216 (2015).*

Introduction

Photon momentum ➡ Optical force



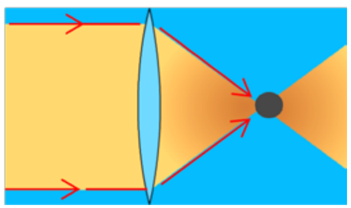


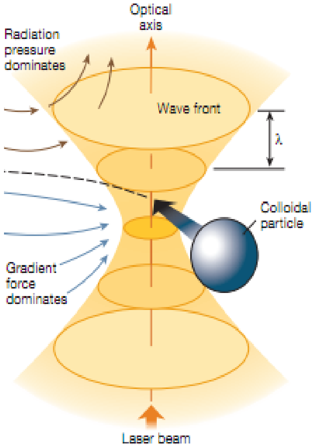
$$\vec{p} = \hbar\vec{k} = h/\lambda$$

$$F = \frac{\Delta p}{\Delta t} = A\frac{I}{c}$$

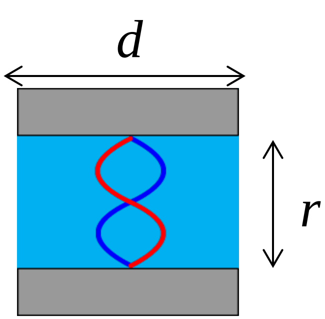
How to enhance optical force ?

(a) Focus: use a lens



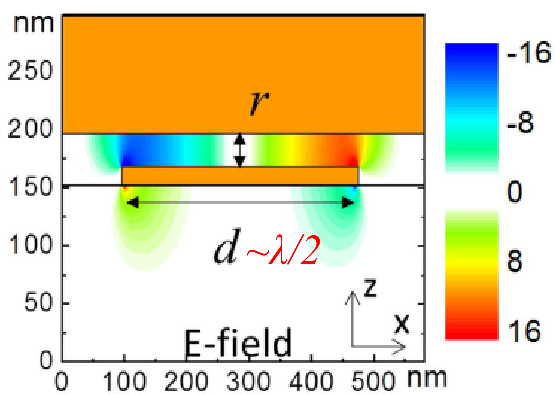


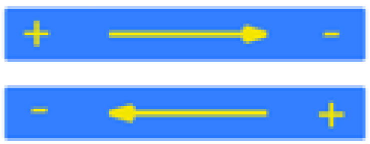
(b) Resonance: use a cavity



Fabry perot resonator

Plasmonic cavity and resonator

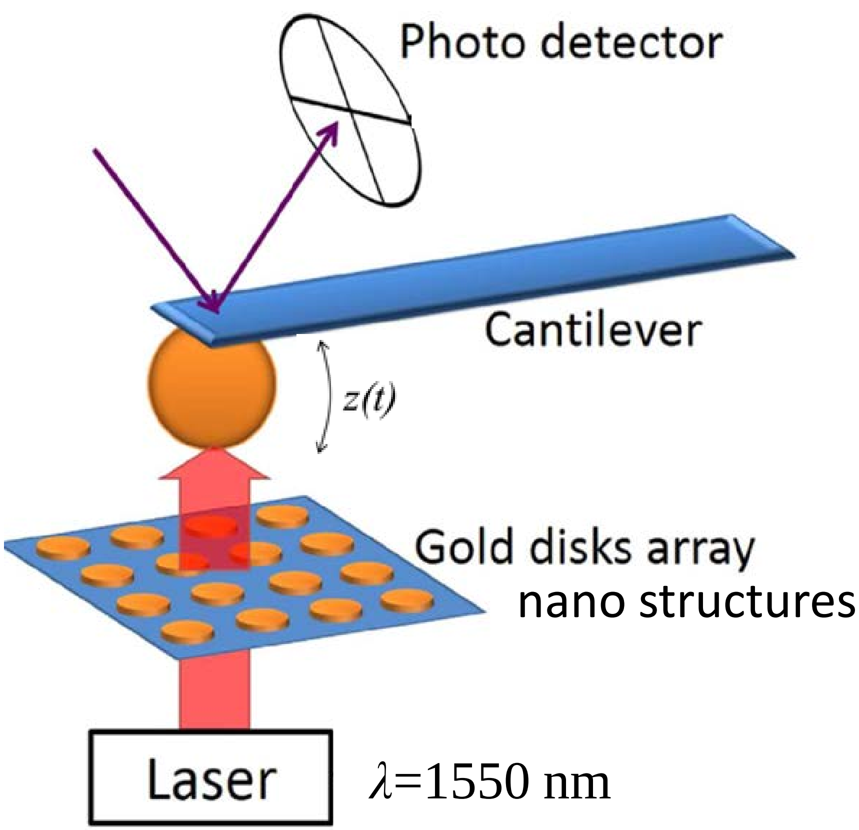


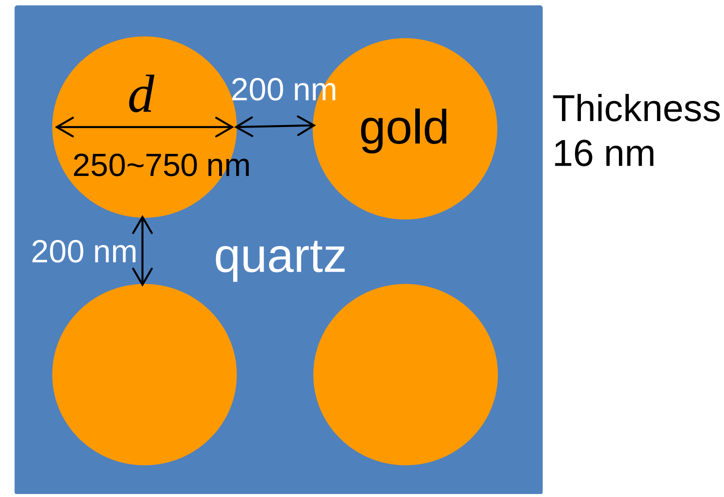


*Liu, H. et.al., PRL. **106**, 087401 (2011).*
*Marcet, Z. et al. PRL.**112**, 045504 (2014).*

Experiment

Designed optical cavity with AFM

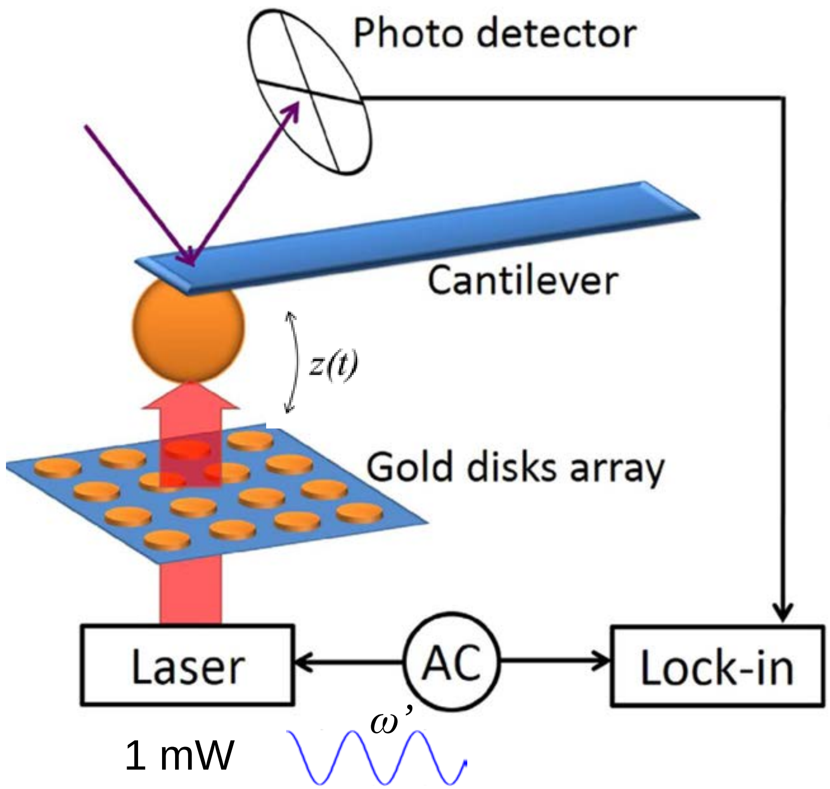




Magnified top view of gold disks array

Gold coated glass sphere 28.4 μm in diameter on the end of a cantilever

Dynamic mode AFM



$$m\ddot{z}(t)+\xi\dot{z}(t)+kz(t)=F_0\cos(\omega' t)+f_B(t)$$

Optical force (F_0)   Brownian force (f_B)

$$z(t)=A\cos(\omega' t+\varphi)$$

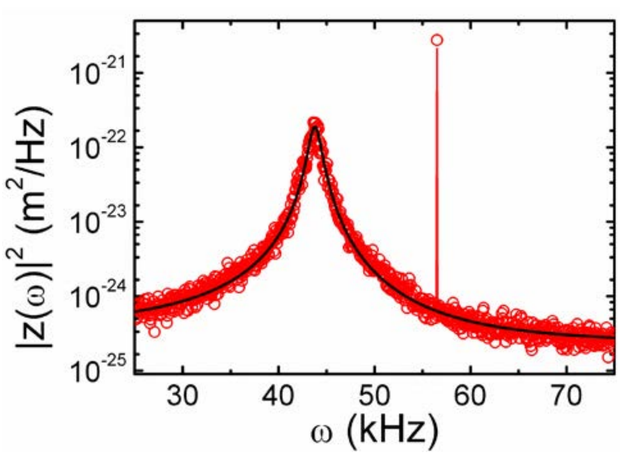
Force: $F_0 = Am\sqrt{\left(\omega_0^{\,2}-\omega'^2\right)^2+(\omega'\xi/m)^2}$

The power spectrum density (PSD):

$$|z(\omega)|^2=\frac{F_0^{\,2}/m^2 2\pi\delta(\omega-\omega')+2k_BT\xi/m^2}{\left(\omega_0^{\,2}-\omega^2\right)^2+\left(\omega\xi/m\right)^2}$$

Force sensitivity: AC ~ 0.1 pN

$F_0 = kz$ DC > 10 pN



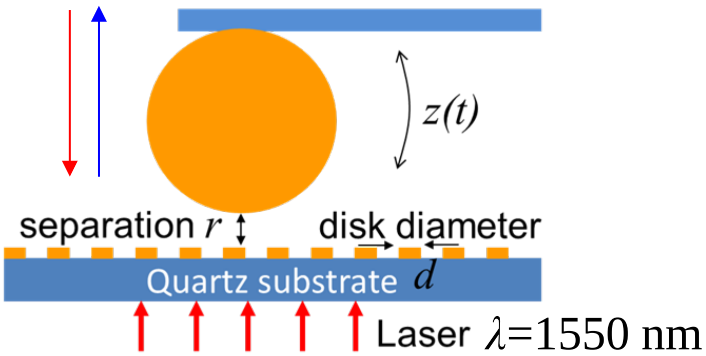
$\xi(r), m, \omega_0 = \sqrt{\frac{k}{m}}$

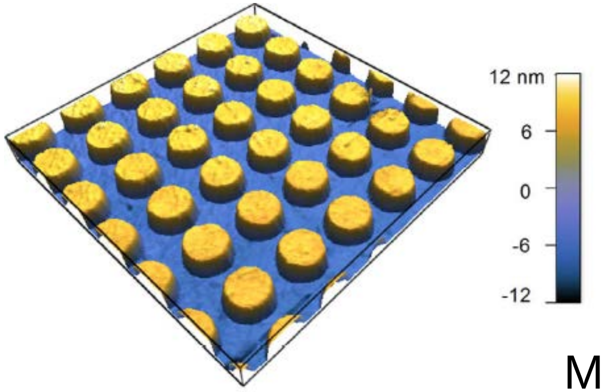
measured form PSD fitting.

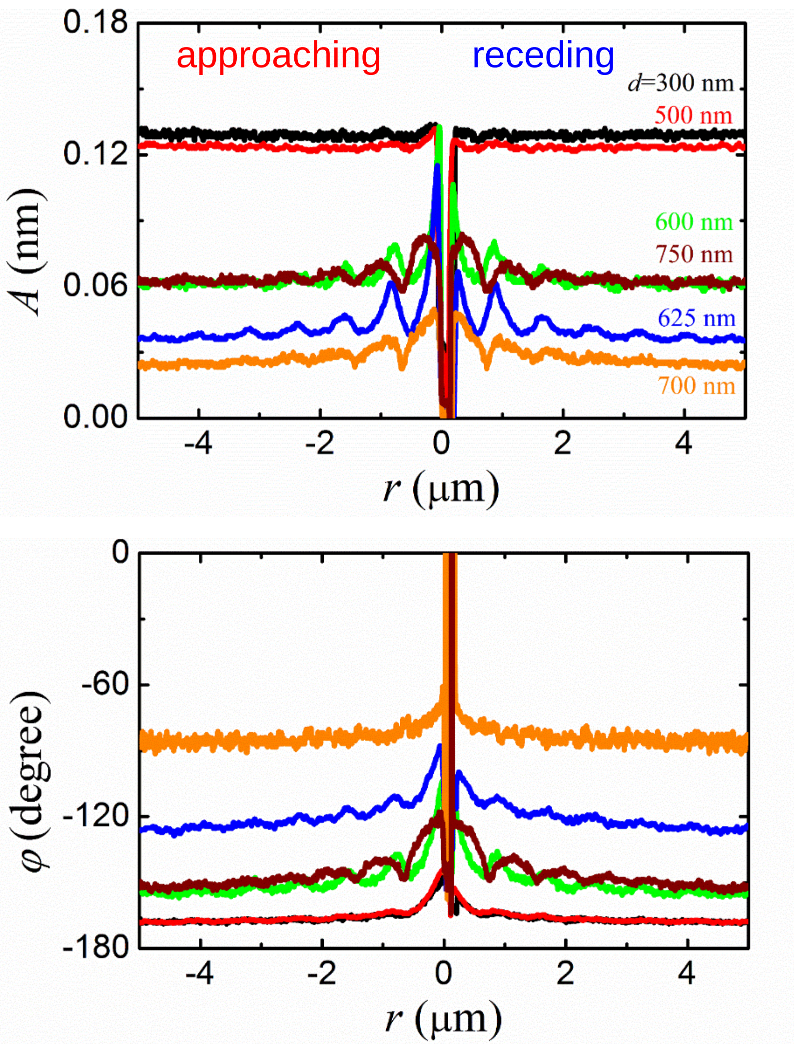
Results

Important variables:

- disk size d (250~750 nm)
- the cavity separation r



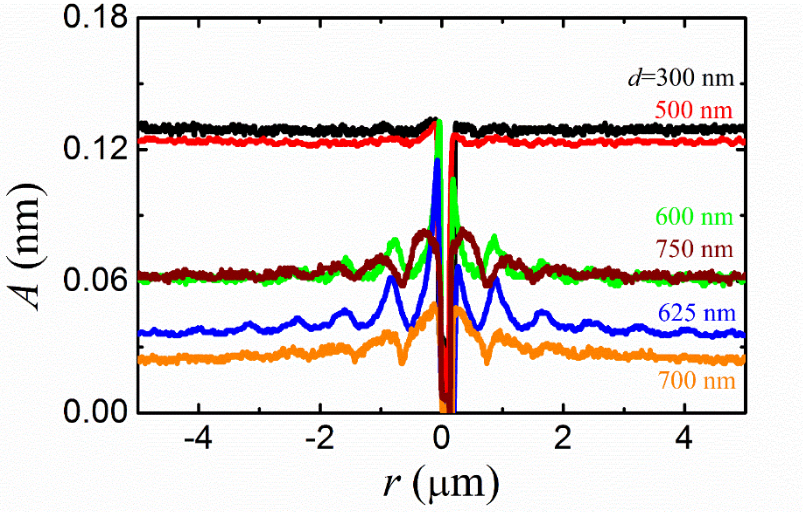


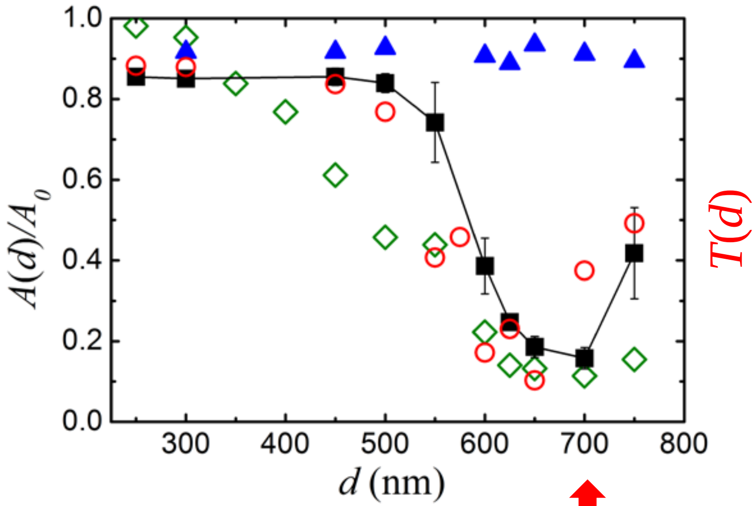


Measured displacement amplitude A and phase delay ϕ.

Results

Far-field (r>3 μm) amplitude and optical transmission





$A \sim F_0 \sim$ Intensity $\sim$ Transmission $T(d)$

Normalized displacement amplitude: $A(d)/A_0$

$A(d)$: measured amplitude of pattern with disks diameter d

A_0: measured amplitude of quartz substrate without pattern

Excitation of the plasmonic dipole mode of the gold disks.

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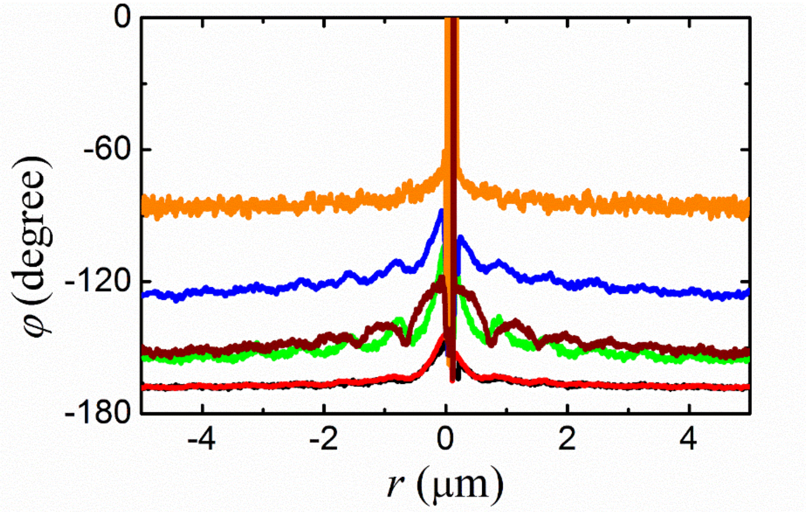
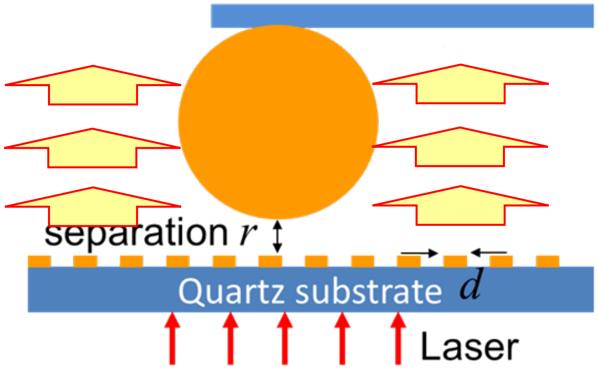
Results

Far-field (r>3 μm) phase delay and thermal effect





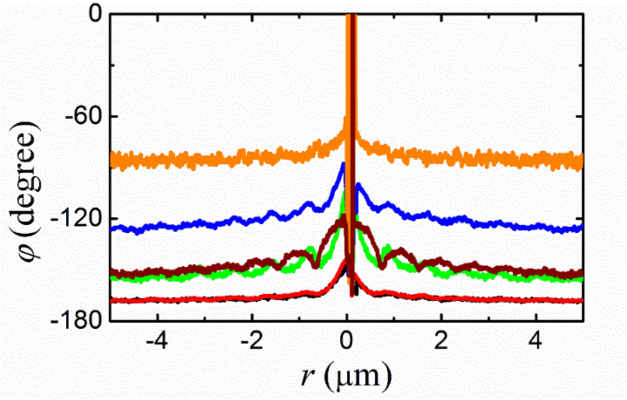
Reduce thermal effects:
a. minimum power 1 mW
b. reflective layer on cantilever beam
c. driving frequency 55 kHz

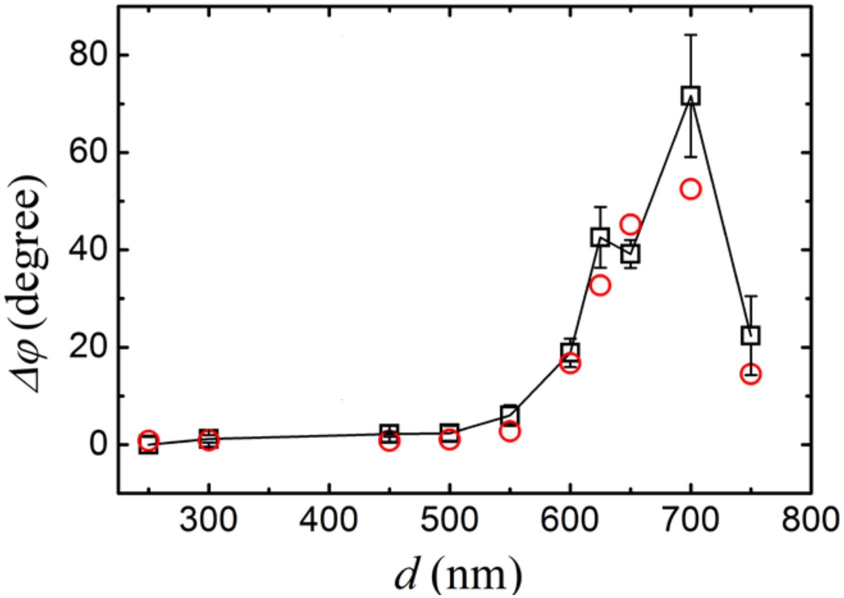
Heat generated from the bottom,
transfers by thermal diffusion,
is absorbed by the cantilever beam,
makes the uneven bending.

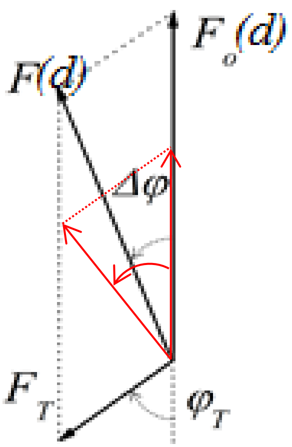
Thermal effects do there !

Results

Far-field (r>3 μm) phase delay and thermal effect







$$F\cos(\omega t + \Delta\varphi) = F_o - F_T\cos(\omega t - \varphi_T)$$

Extra thermal force F_T with phase delay φ_T .

$\varphi_T \approx \omega\tau_0,\ \tau_0$ is the thermal diffusion time in air.

$F_o(d)$ ~ *Transmission* $T(d)$

$\alpha=(F_T/F_o)T(d)=0.17$ $F_o \approx F$

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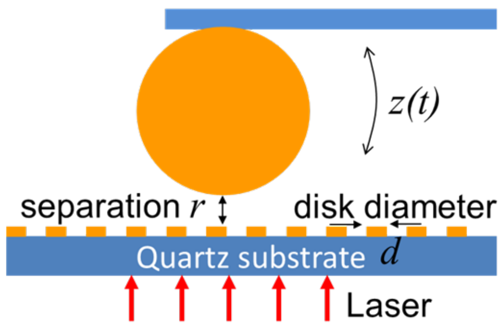
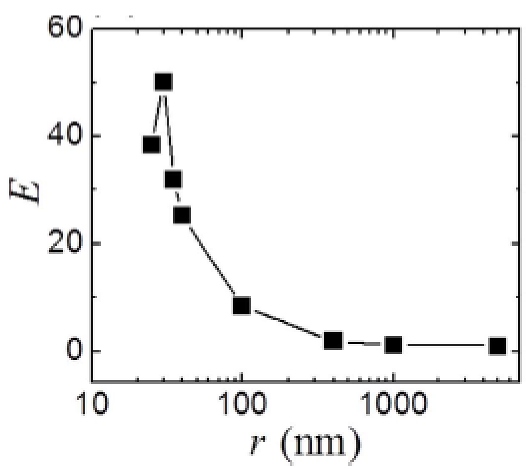
Results

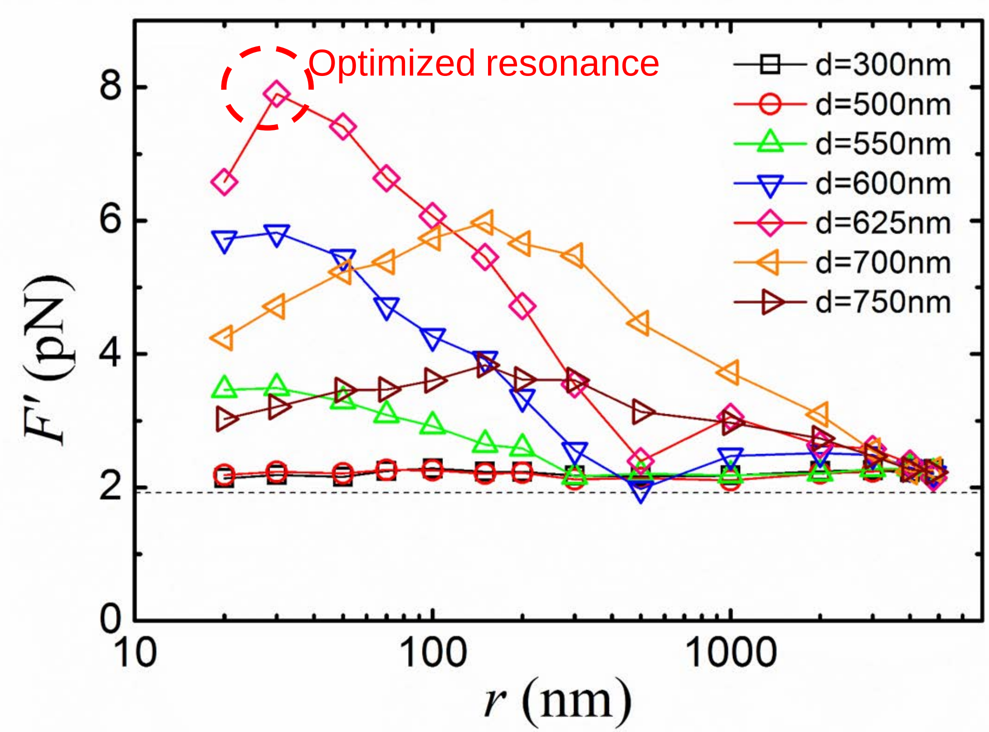
Near-field (r<0.5 μm) optical force enhancement





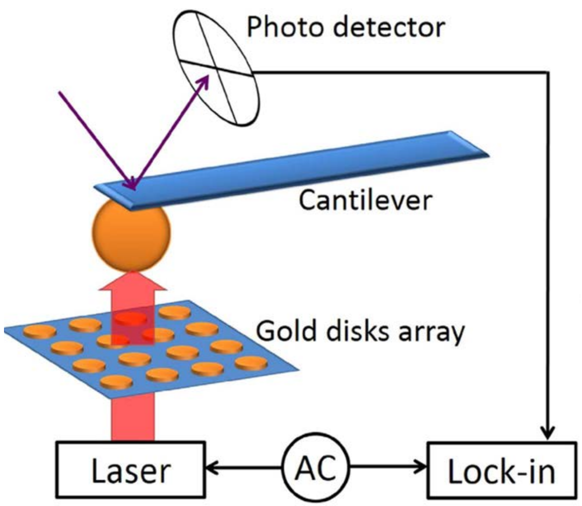
Force: $F_0 = Am\sqrt{\left(\omega_0^{\,2} - \omega'^2\right)^2 + (\omega'\xi/m)^2}$

$F' = F_o T(625)/T(d)$



Enhancement factor E under the experimental resonant conditions with λ=1550 nm, d=567 nm and r=30 nm is E=18.

Conclusion



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- **Develop a sensitive dynamic mode AFM**

  Force: pN, Size: nm, versatile.
- **Construct nano pattern plasmonic resonant cavity**

  a. The gold dots diameter *d~1/2* λ;

  b. The cavity separation *r*.
- **Enhanced optical force in near filed**

  Enhancement factor ~18.
- **Thermal effect is unavoidable**