2023/3/27

OIST

Theodoros D. Bouloumis

# Metamaterial Plasmonic Tweezers for Trapping Quantum Dots

Light – Matter Interactions for Quantum Technologies Unit
Okinawa Institute of Science and Technology, Okinawa, Japan

# Contents

# 1) Background

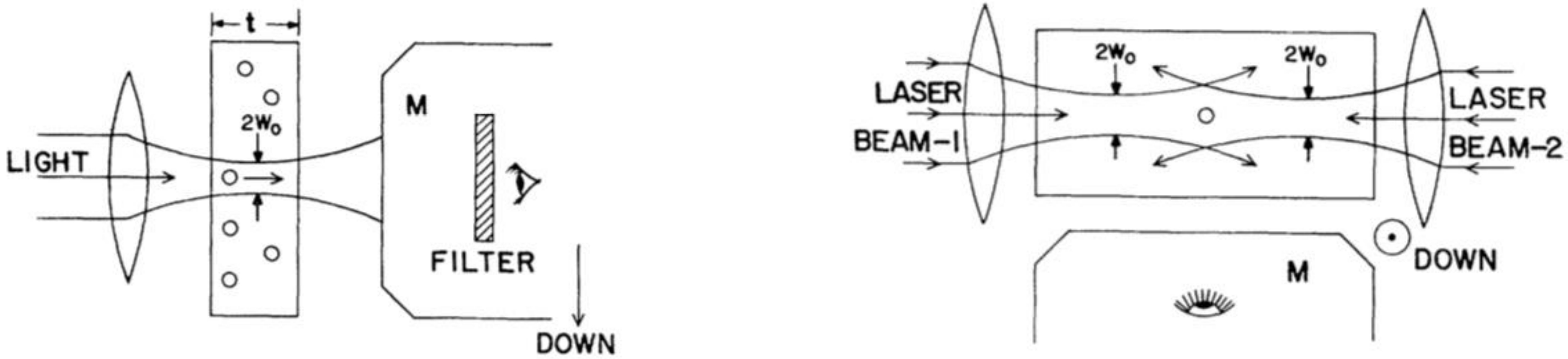
Kepler – 1619 – Comet tail always point away from the sun

Theo – 2020 - Comet NEOWISE

Photons no mass but yes momentum

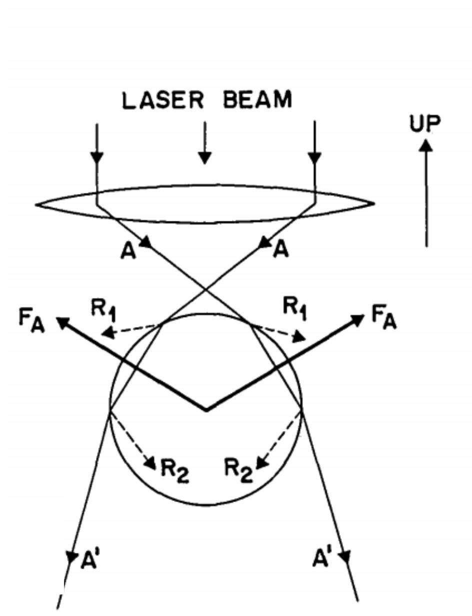
**Transfer of momentum from light to objects results in the light forces**

# Arthur Ashkin
## 1970



A. Ashkin Physical Review Letters, 24, 4, (1970)

## 1986



A. Ashkin et al. Optics Letters, 11, 5, (1986)

## 2018

# 2) Limitations

**Rayleigh regime *(r<<λ)*** *Dipole approximation*

$$\vec{F} = \frac{1}{4}\alpha'_d \nabla |\vec{E}|^2 + \frac{\sigma_{ext,d}}{c}\vec{S} + \frac{c\epsilon_0 \sigma_{ext,d}}{4\omega i}\nabla \times (\vec{E} \times \vec{E}^*)$$

gradient

scattering

spin-curl

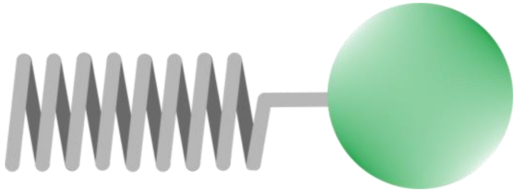
$a'_d = Re(a_d) \propto \mathrm{r}^3$

$\sigma_{ext,d} \propto Im(a_d) \propto \mathrm{r}^6$

Polarization gradients

100nm → 10nm

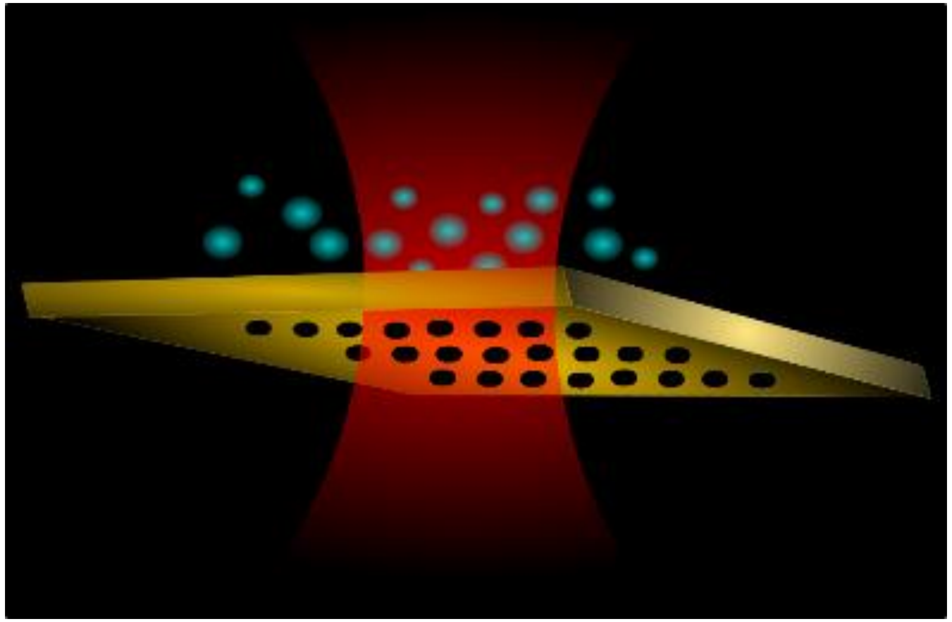
*$F_{grad}$/1000*



Trap stiffness $k_m = 2\frac{\alpha_d{}'}{c\varepsilon_0}\frac{I_0}{w_0^2}$

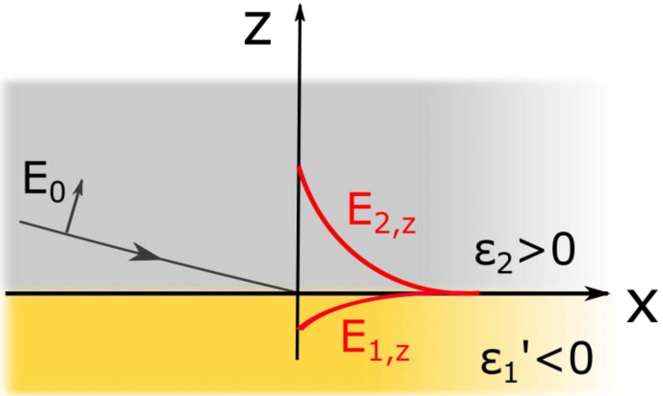
**Optical tweezers cannot trap particles smaller than a few hundred nm**

# 3) Plasmonic Optical Tweezers (POTs)

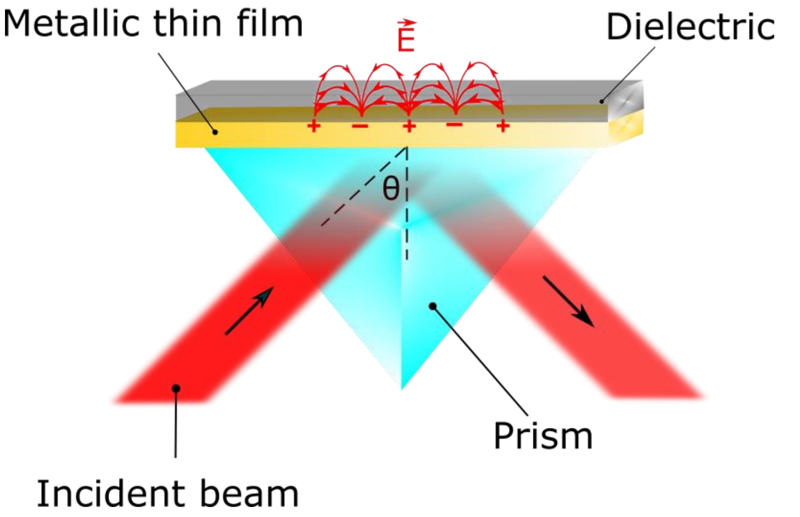


Surface Plasmons

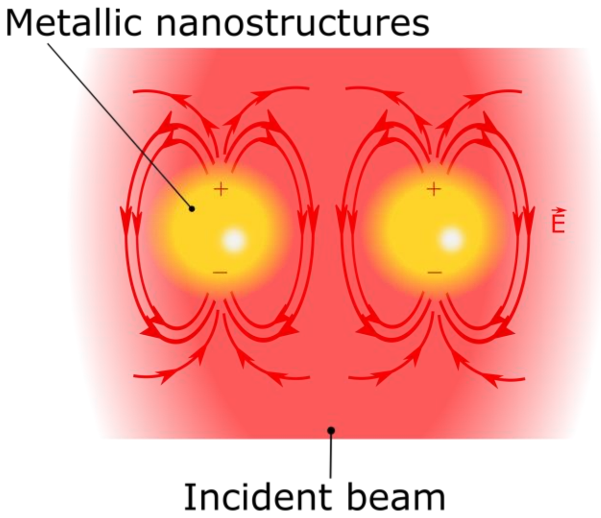
$$\vec{F}_{grad} = \frac{1}{4}\alpha_d'\nabla|\vec{E}|^2$$



## Surface plasmon polaritons (SPPs)



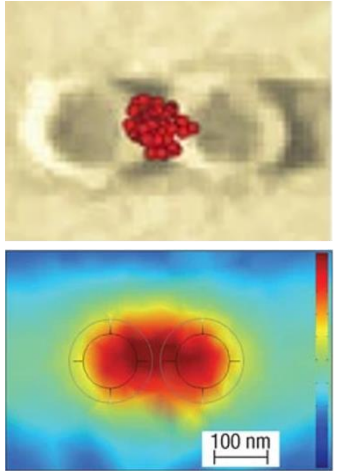
## Localised surface plasmons (LSPs)



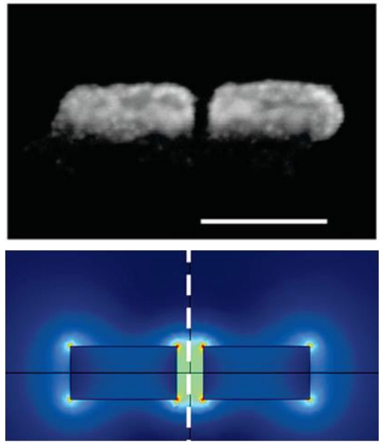
T.D.B. and S.N.C. Applied Sciences 2020, 10(4), 1375

**POTs provide stiffer traps, but also result in temperature rise in the solution**

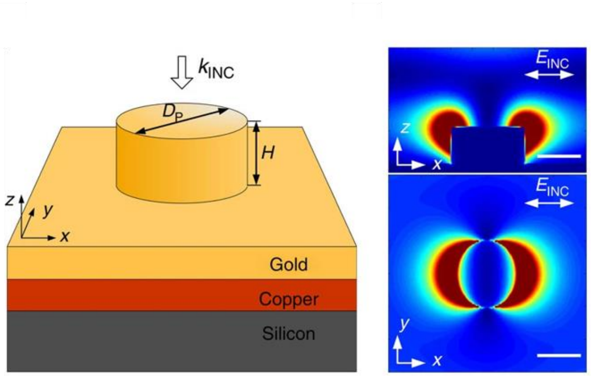
# POT Designs



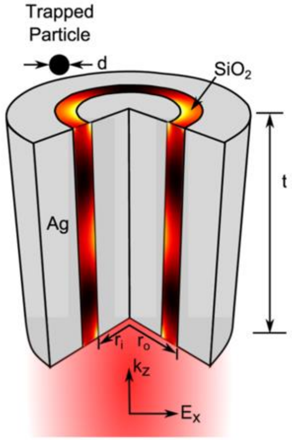
A. N. Grigorenko et al. Nature Photonics 2, 365 (2008).



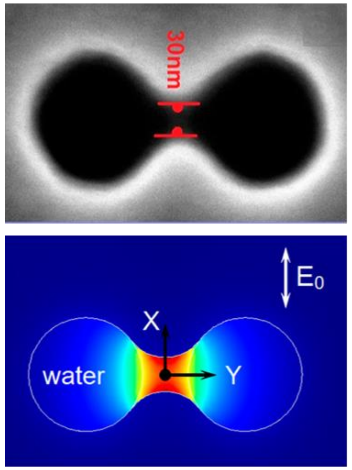
W. Zhang et al. Nano Letters 10, 1006–1011 (2010).



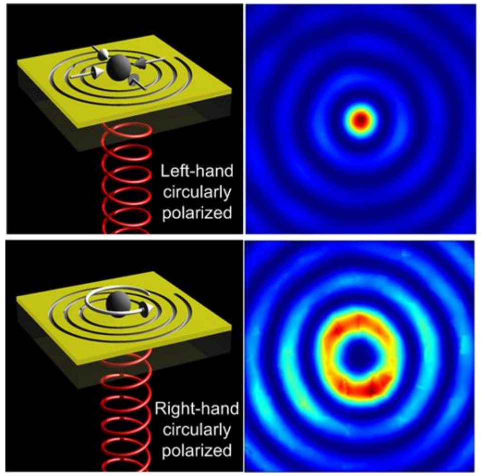
K. Wang et al. Nature Communications 2, 469 (2011).



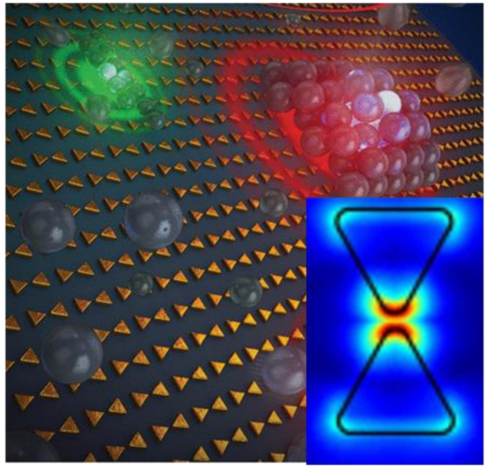
A. A. E. Saleh and J. A. Dionne, Nano Letters 12, 5581–6 (2012).



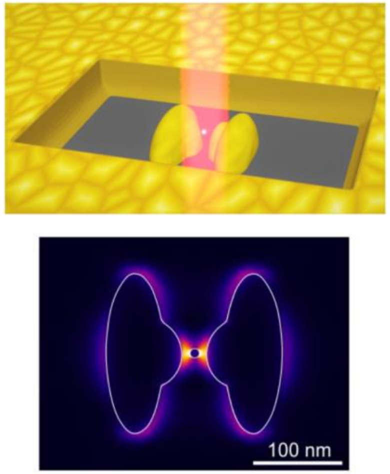
Z. Xu et al. ACS Photonics 5, 2850–2859 (2018).



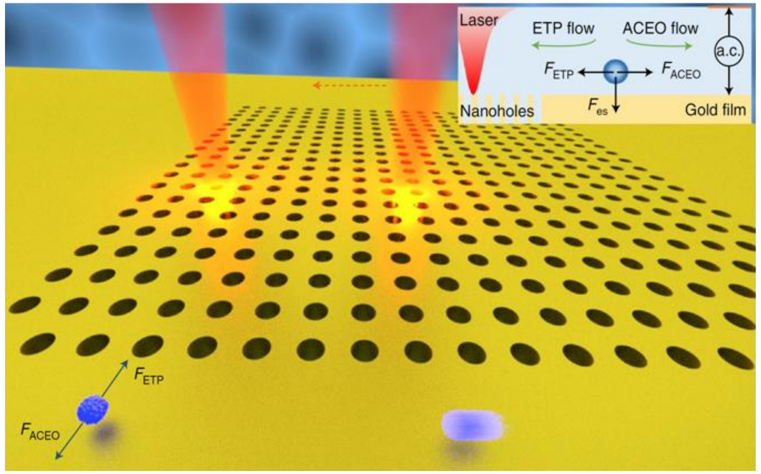
W.-Y. Tsai et al. Nano Letters 14, 547–552 (2014).



B. J. Roxworthy et al. Nano Letters 12, 796–801 (2012).

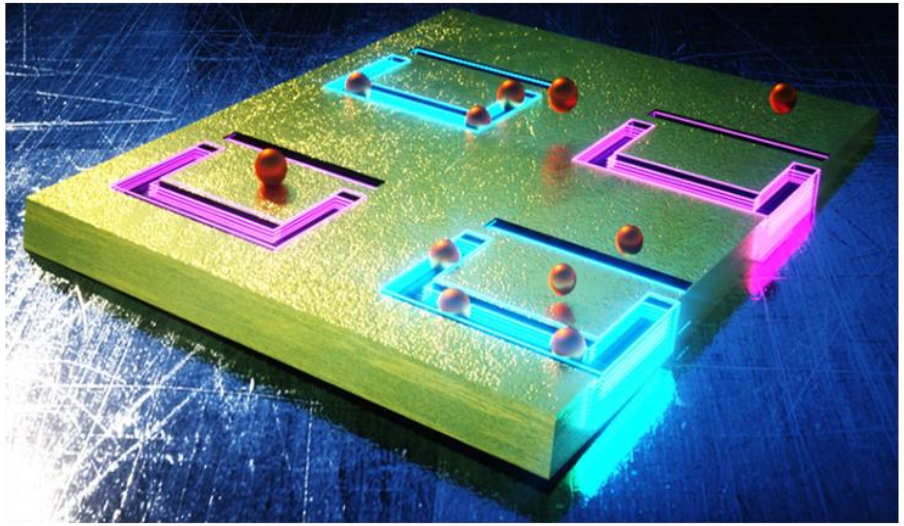


Q. Jiang et al. Nano Letters 21, 16, 7030–7036 (2021)



C. Hong et al. Nature Nanotechnology 15, 908–913 (2020).

# Motivation

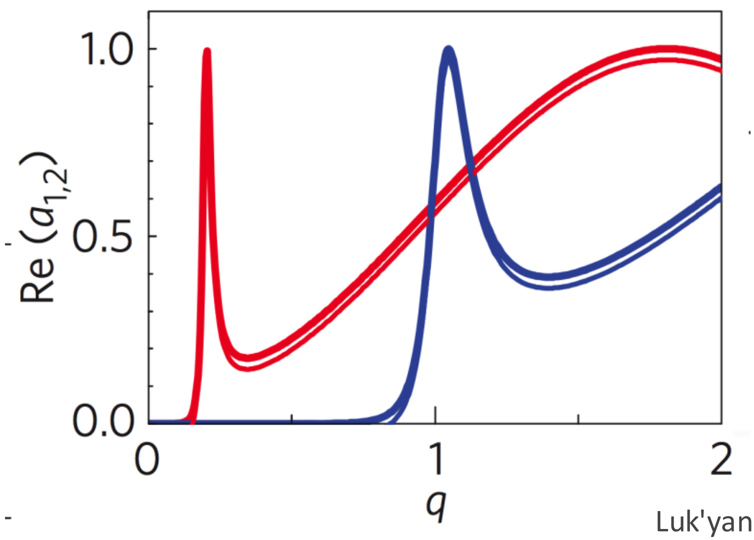


D. G. Kotsifaki et al. Nano Letters 20, 3388–3395 (2020).

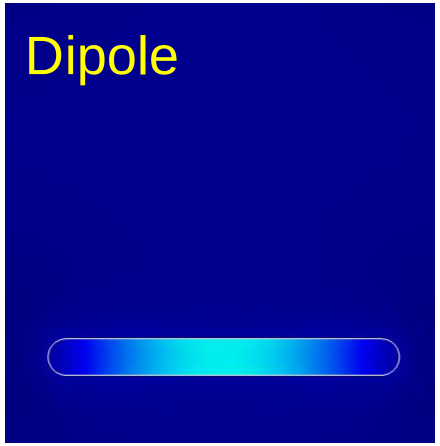
- Advantages and limitations of metamaterial plasmonic tweezers?
- Platform for trapping different particles with very low incident intensities?
- Can be used for enhancing optical properties of localised quantum dots?

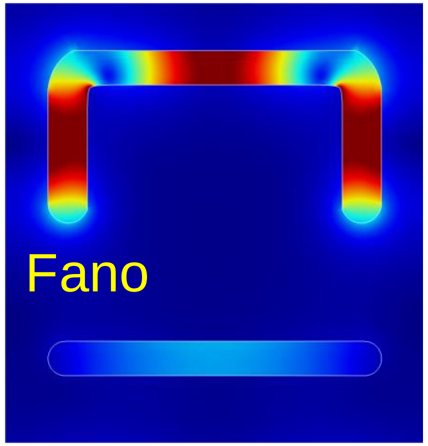
# Contents

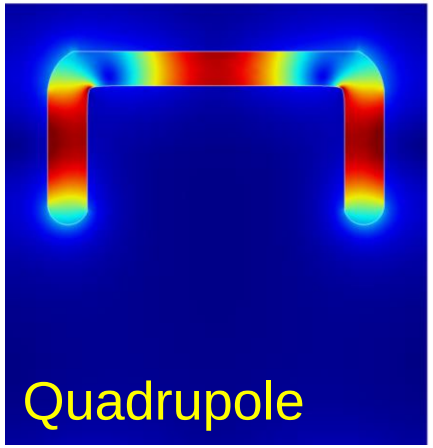
# 4) Metamaterial Theory and Simulations

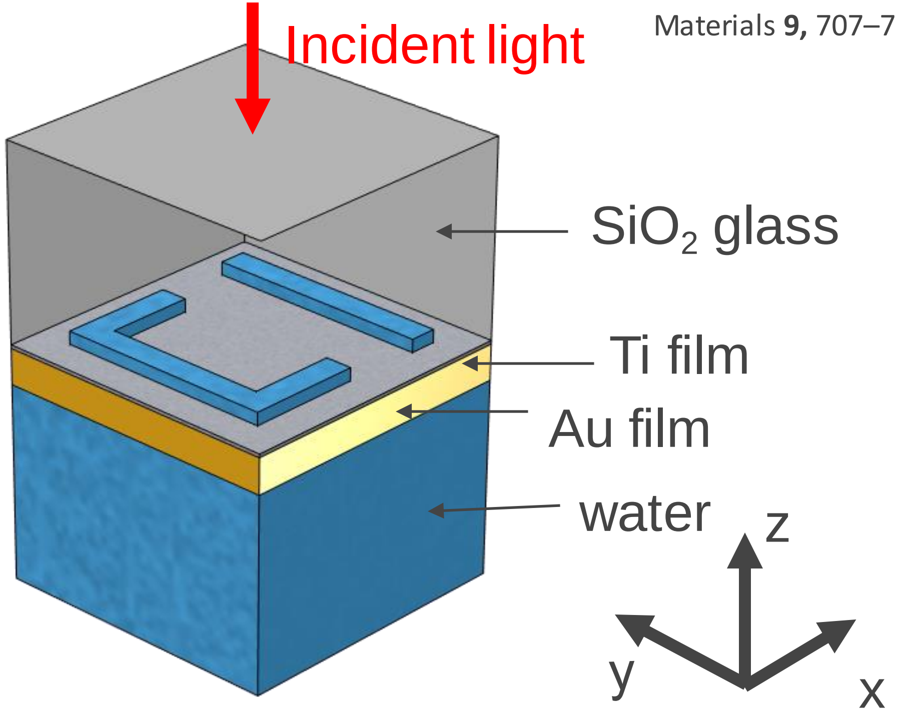


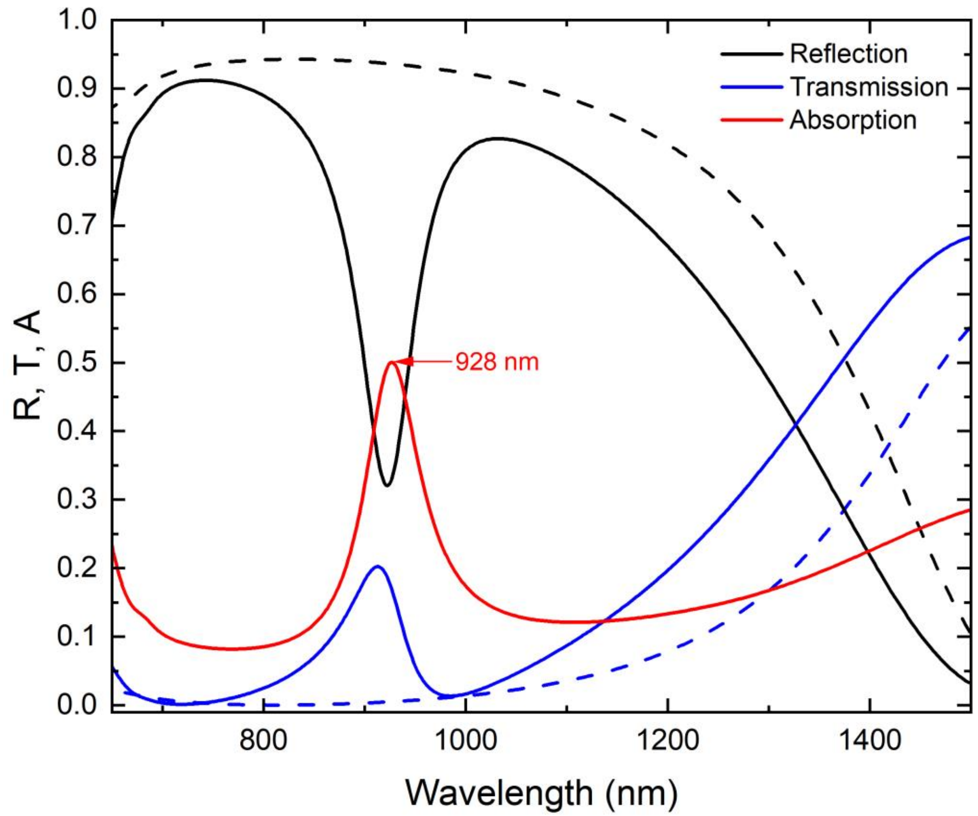
Luk'yanchuk, B., Zheludev, N., Maier, S. et al. Nature Materials **9,** 707–715 (2010)



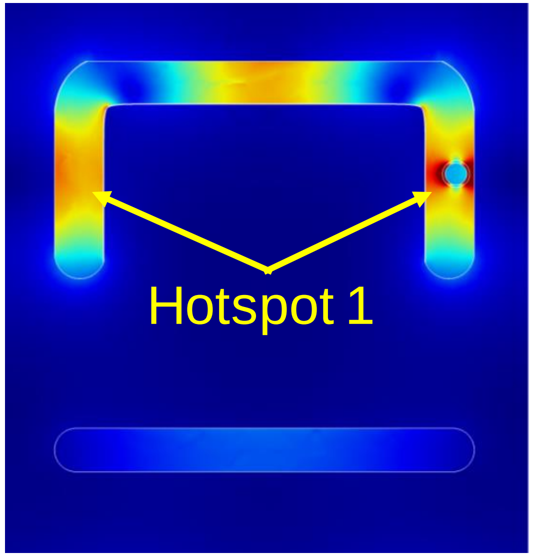


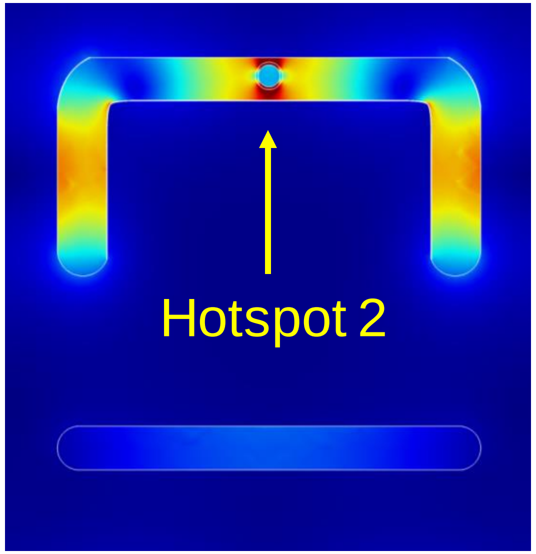


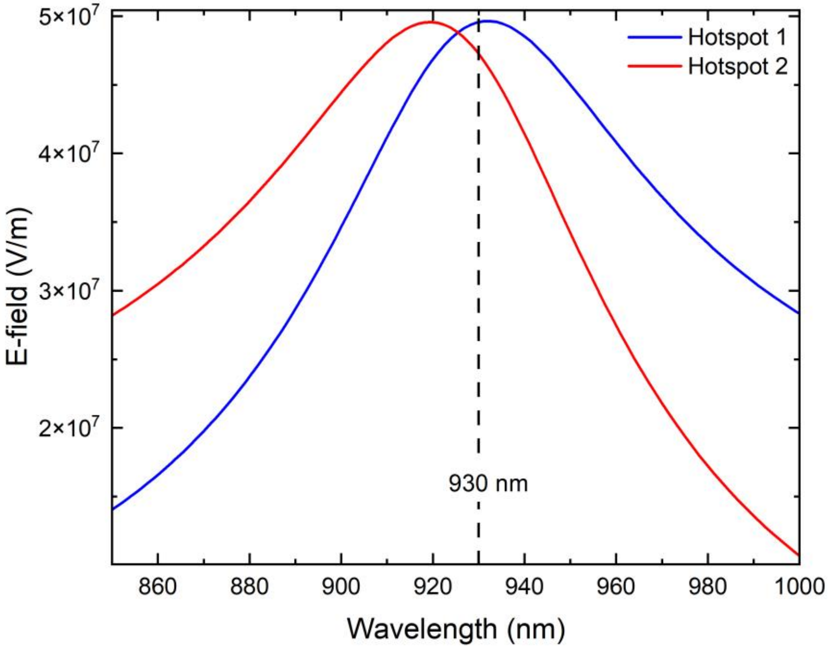


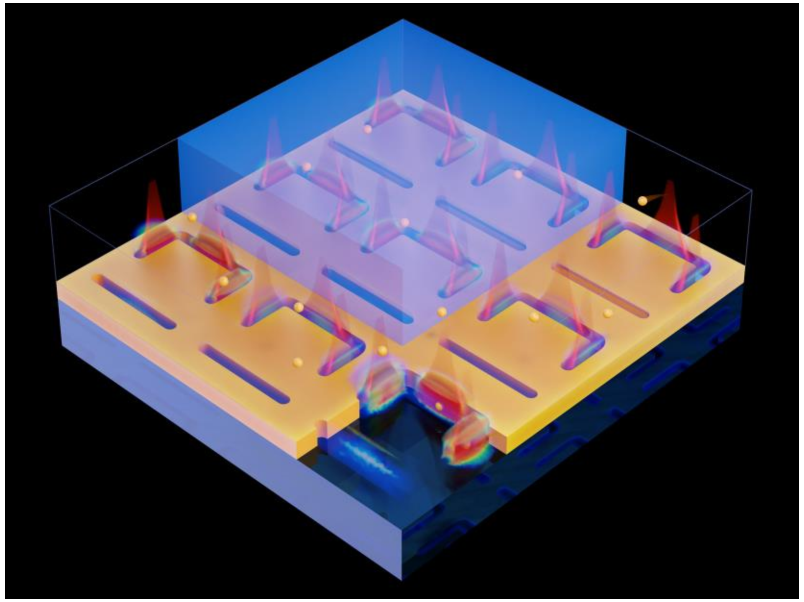


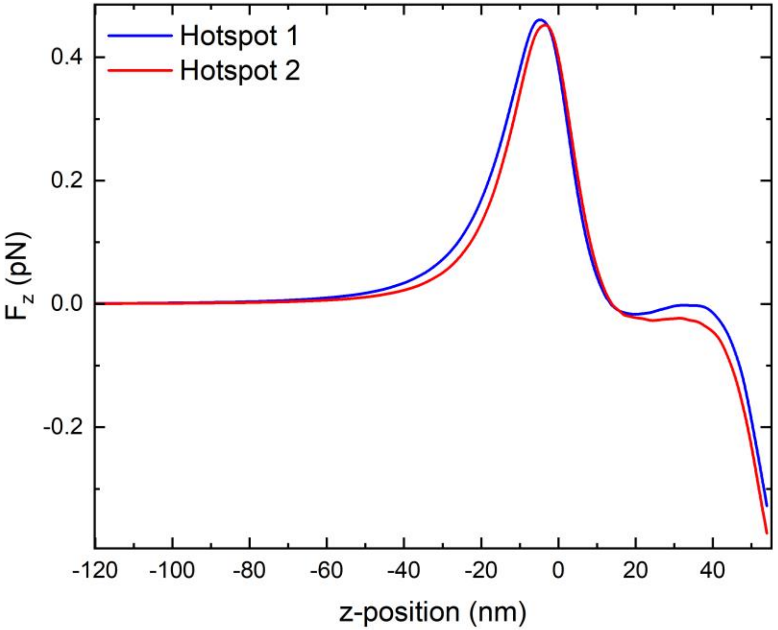
# Simulations

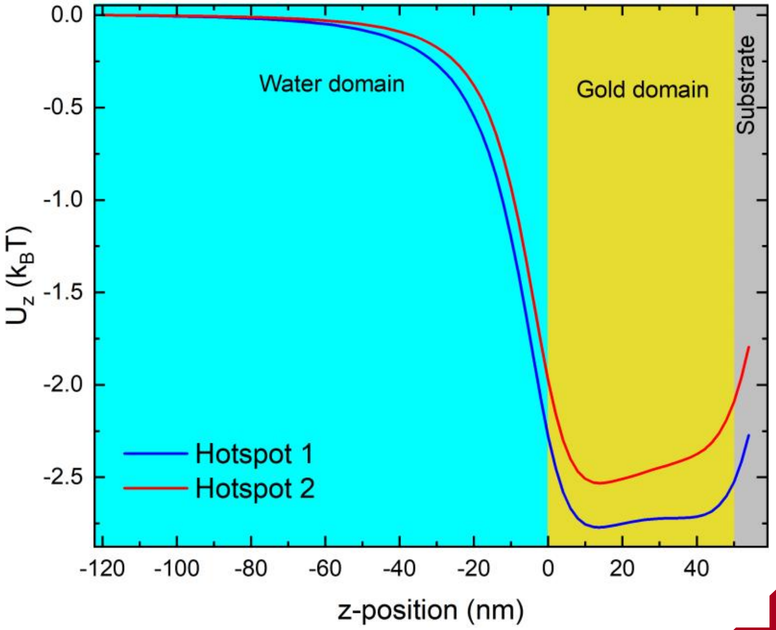






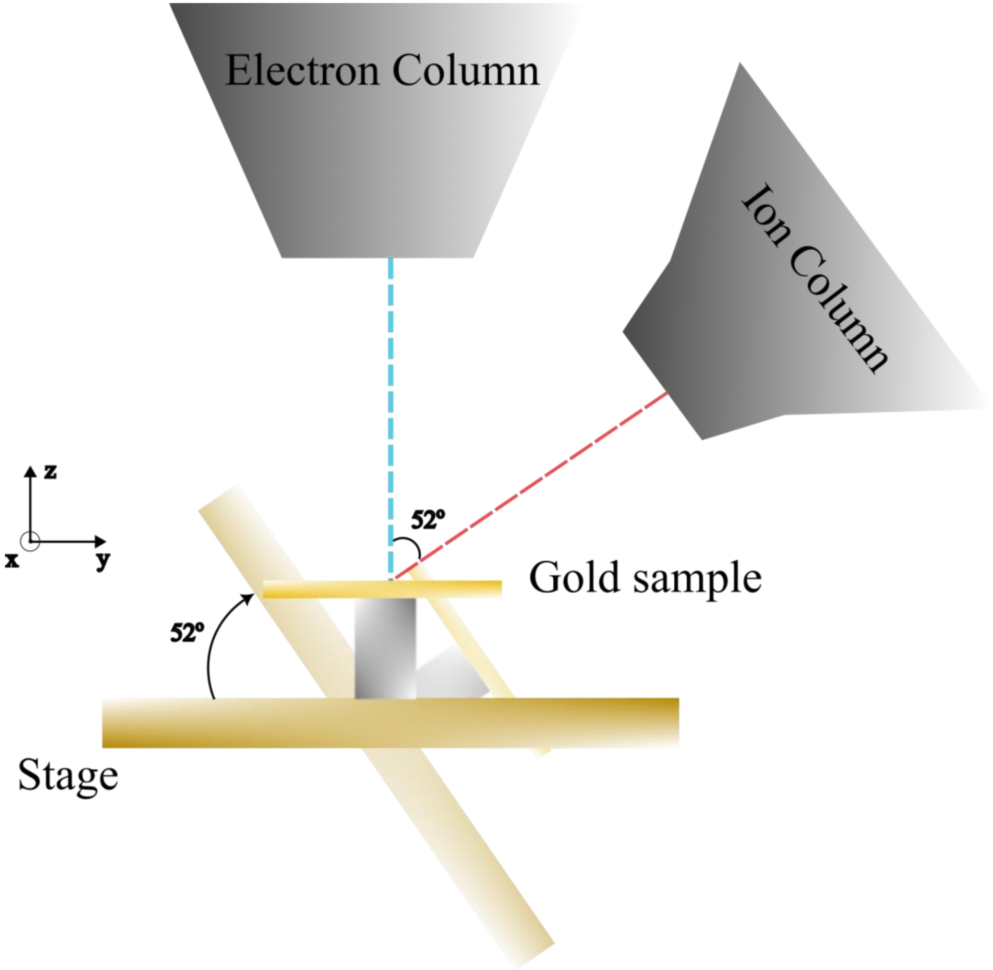


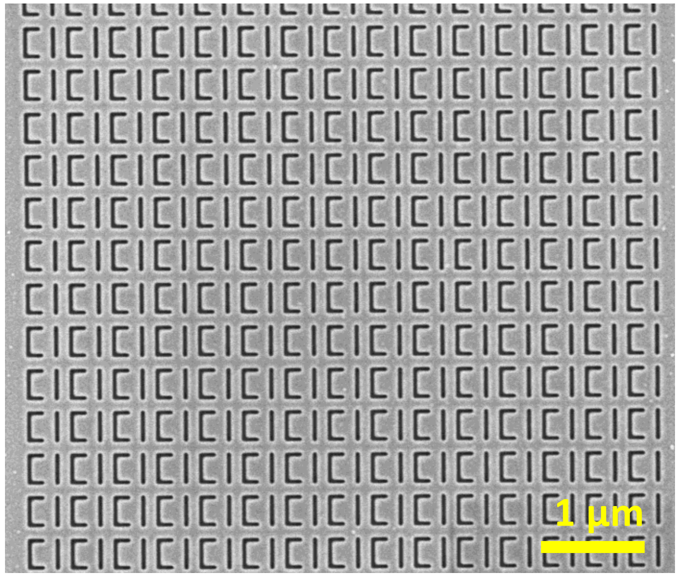


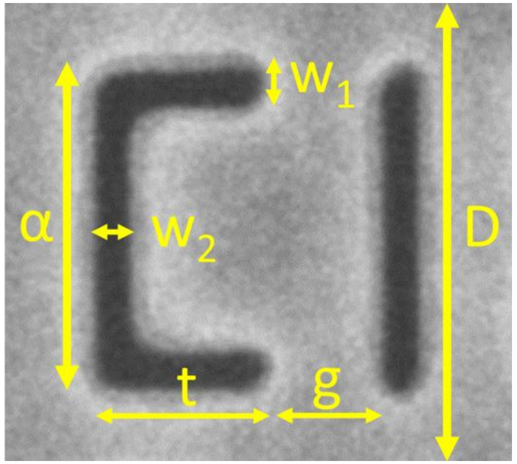


# 5) Fabrication and Characterisation

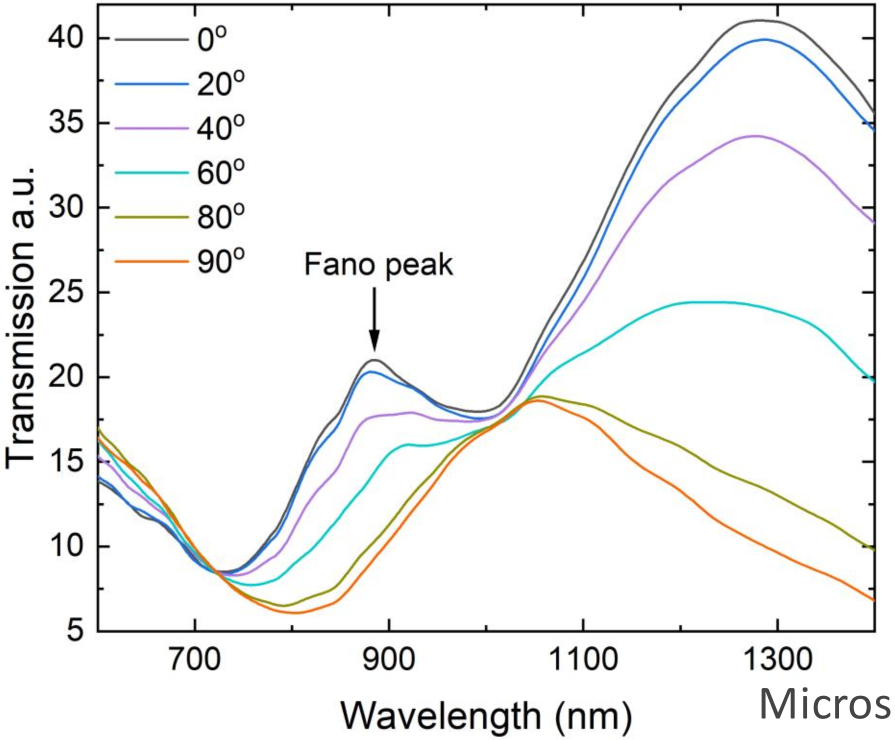
Focused ion beam milling (FIB)





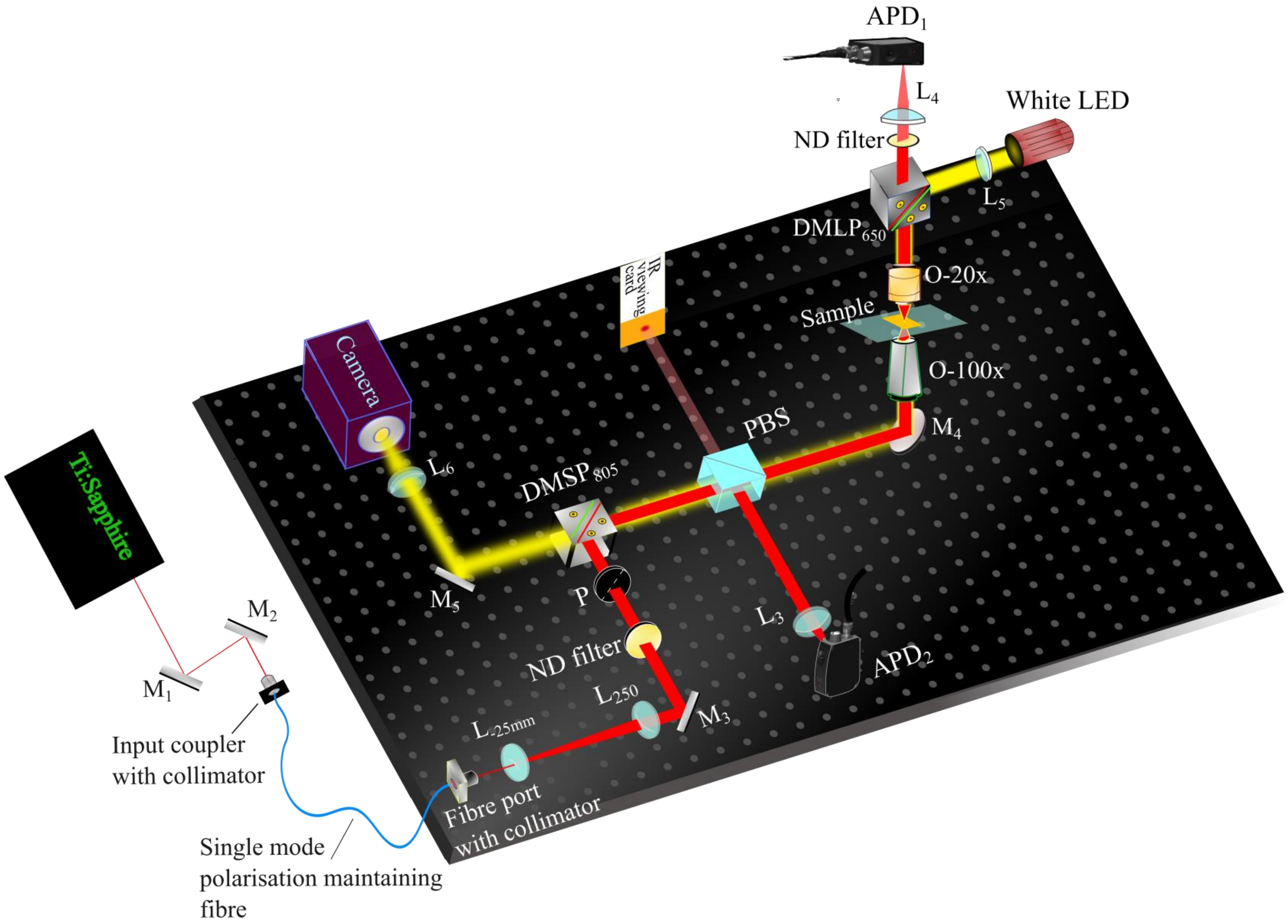


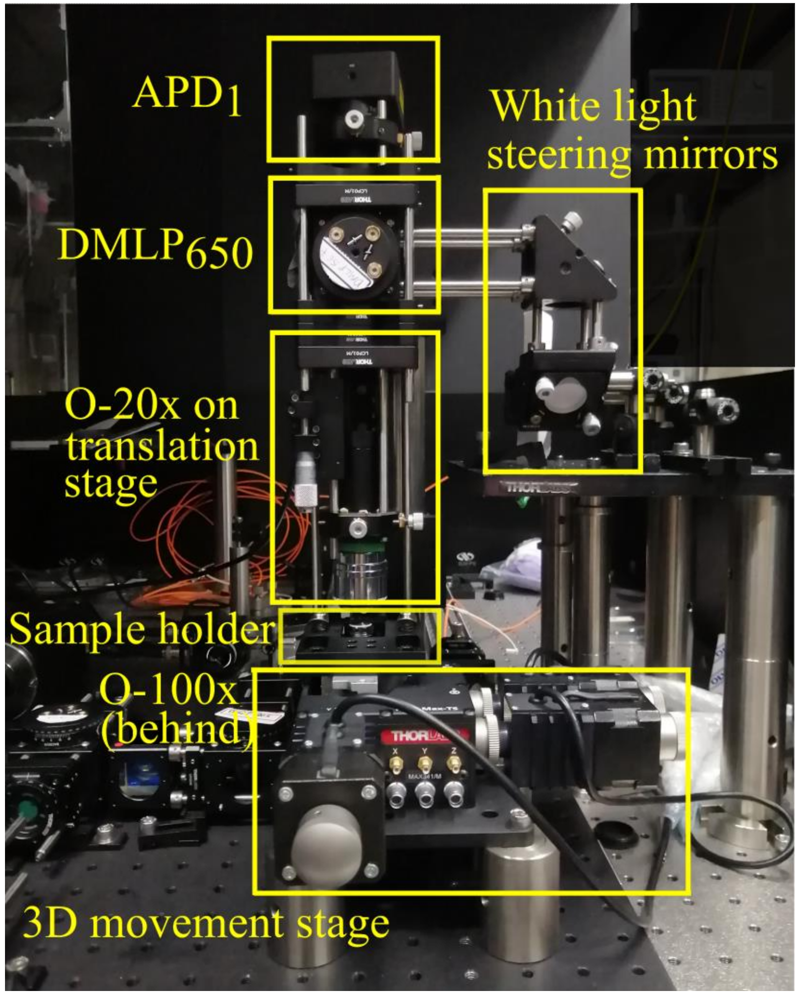
$D = 416 \pm 1.00$ nm
$\alpha = 308 \pm 0.6$ nm
$t = 157 \pm 0.5$ nm
$g = 109 \pm 0.9$ nm
$w_1 = 40 \pm 0.8$ nm
$w_2 = 33 \pm 0.7$ nm

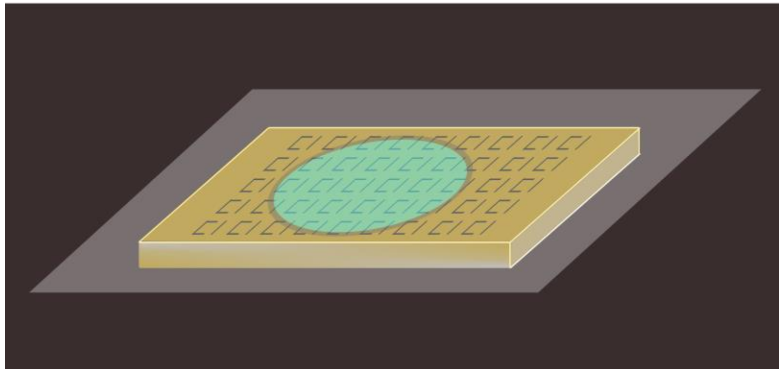


Microspectrophotometry (MSP)

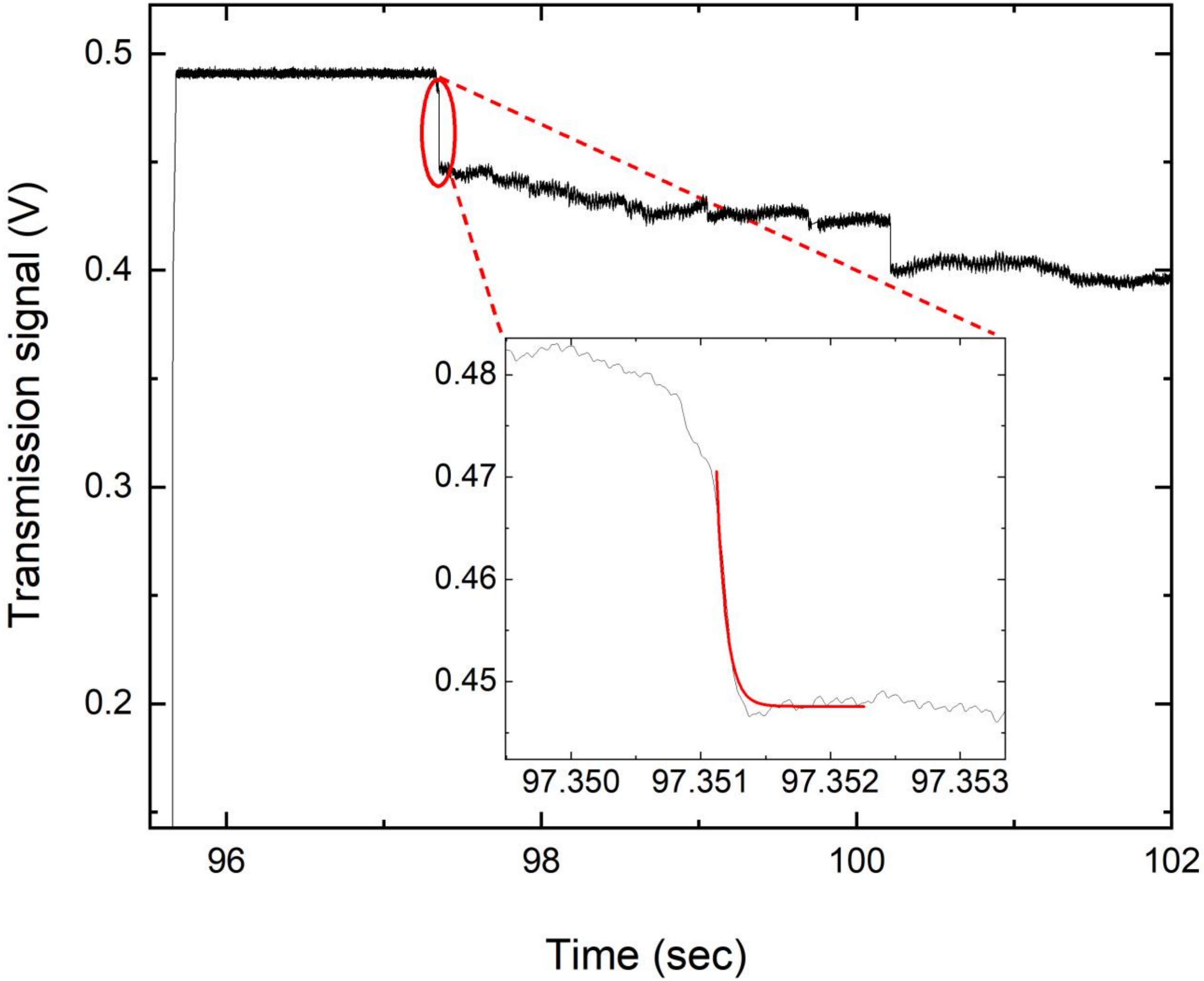
# 6) Experimental Setup







# Signal Analysis



$$x(t) = x_0 + Ae^{-(t-t_o)/\tau}$$

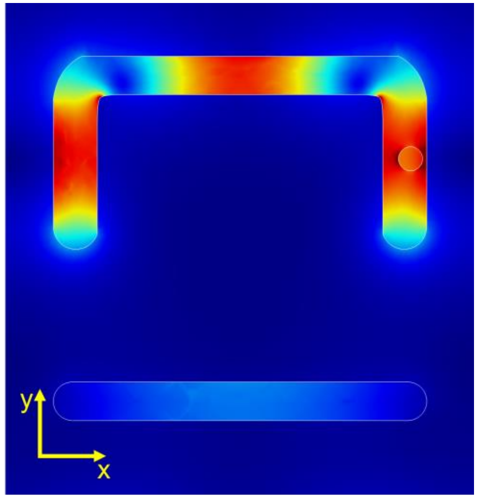
$$\gamma = \frac{6\pi\eta_v r}{1 - \frac{9}{16}\left(\frac{r}{h}\right) + \frac{1}{8}\left(\frac{r}{h}\right)^3 - \frac{45}{256}\left(\frac{r}{h}\right)^4 - \frac{1}{16}\left(\frac{r}{h}\right)^5}$$

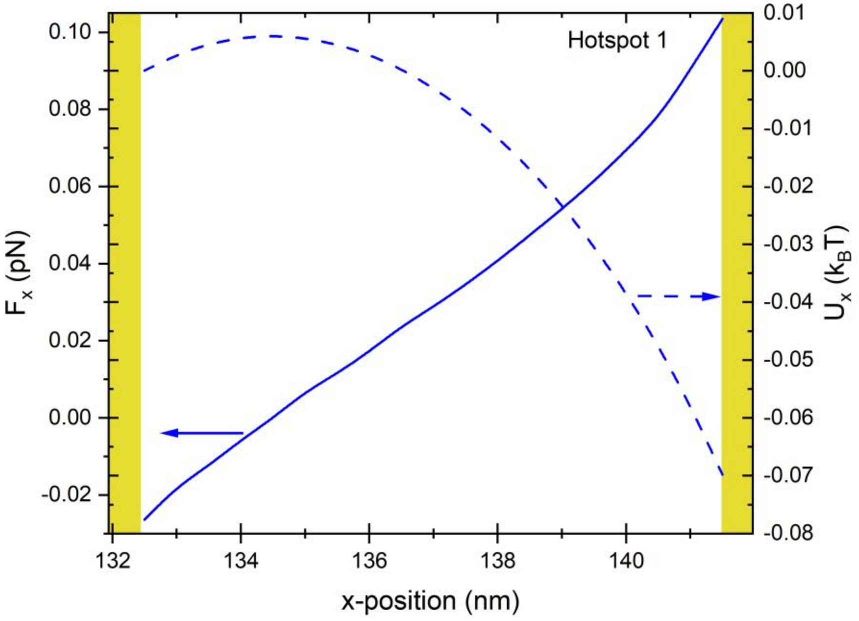
$$\tau = \frac{\gamma}{k_m} \Leftrightarrow k_m = \frac{\gamma}{\tau}$$

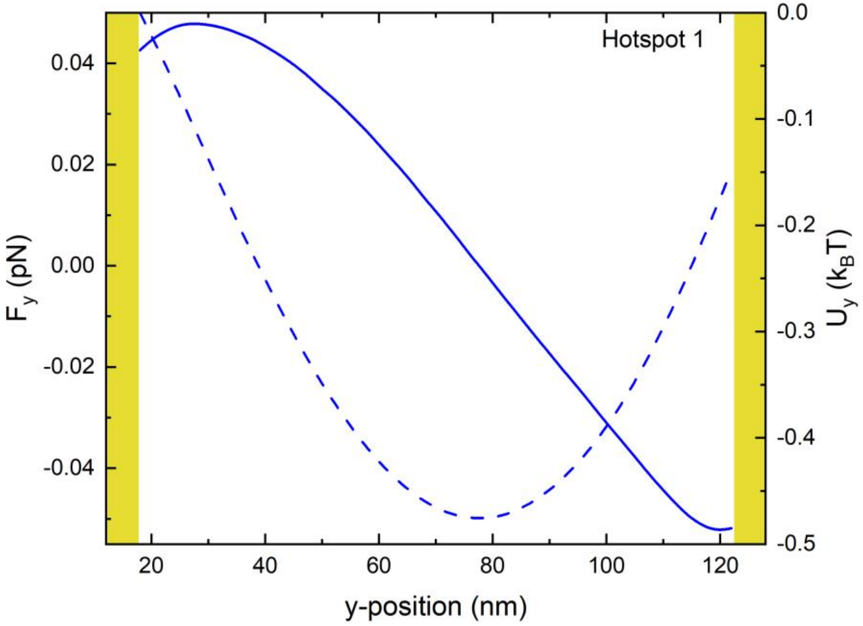
# Contents

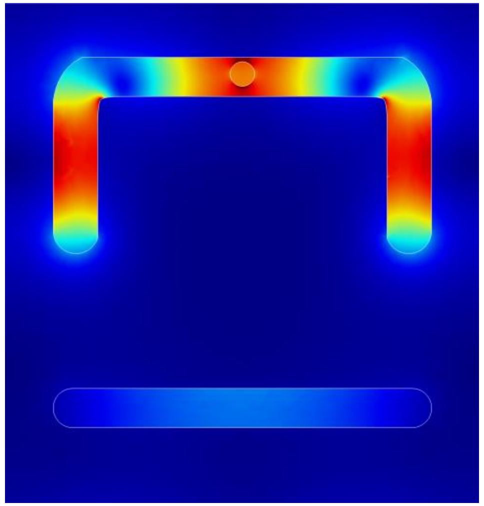
# 7) Calibration with Polystyrene Nanoparticles

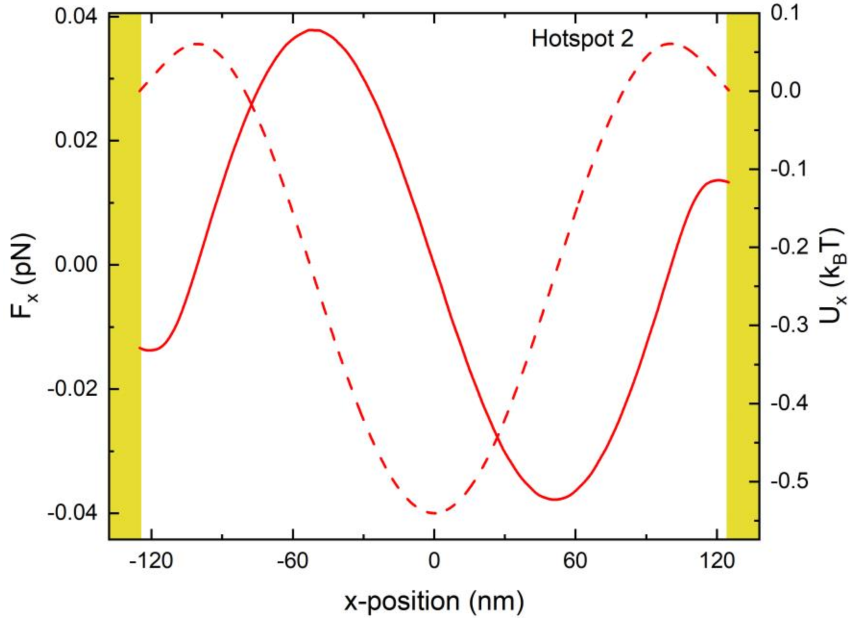
## Optical Forces and Potentials

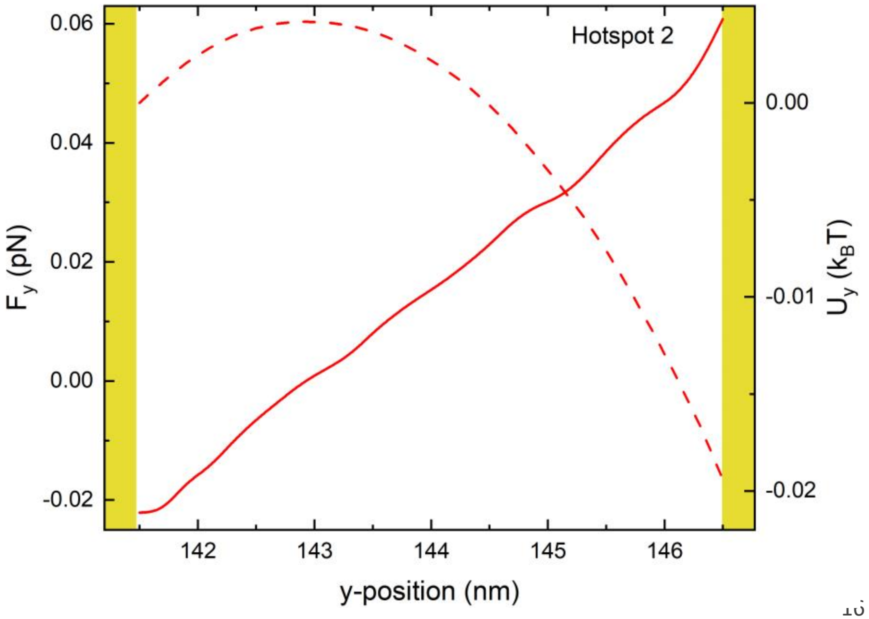




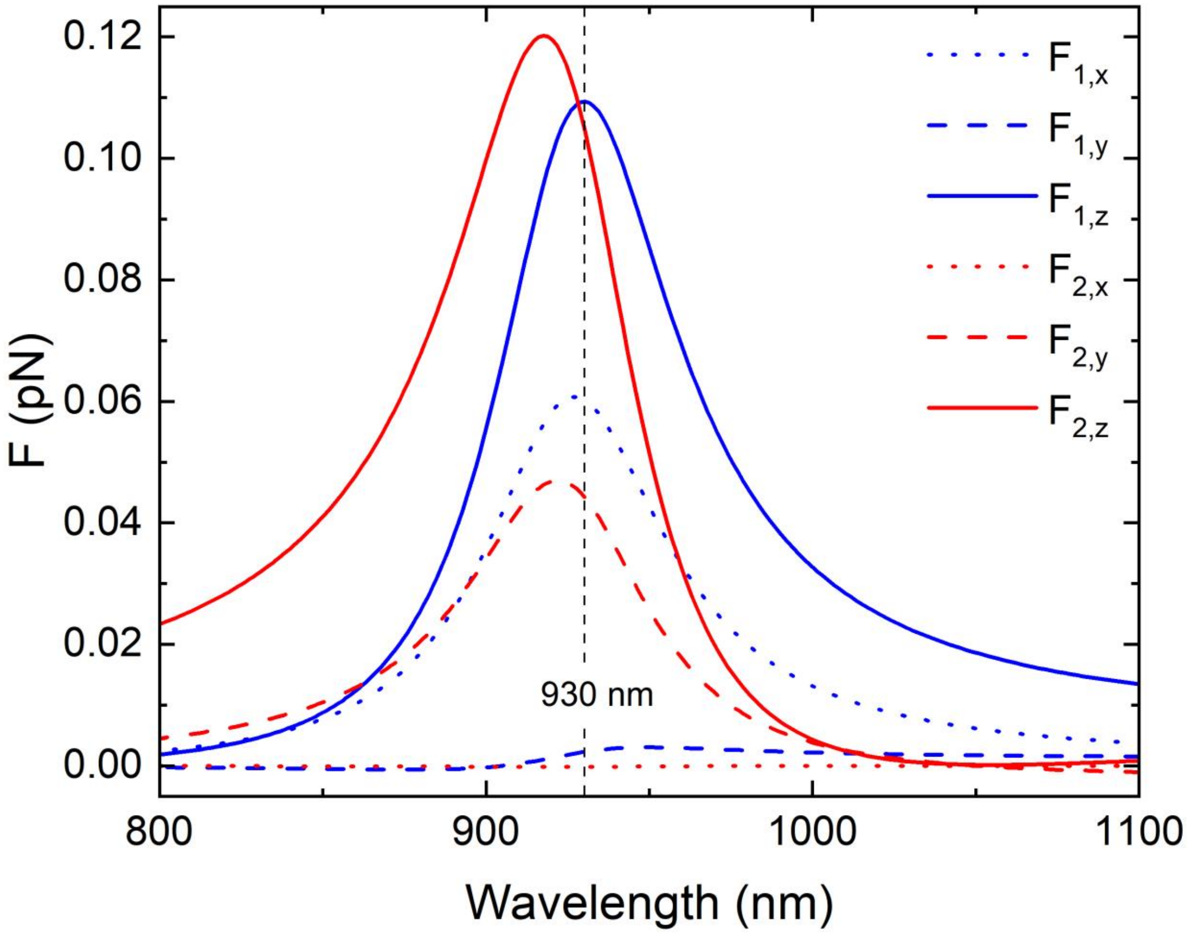


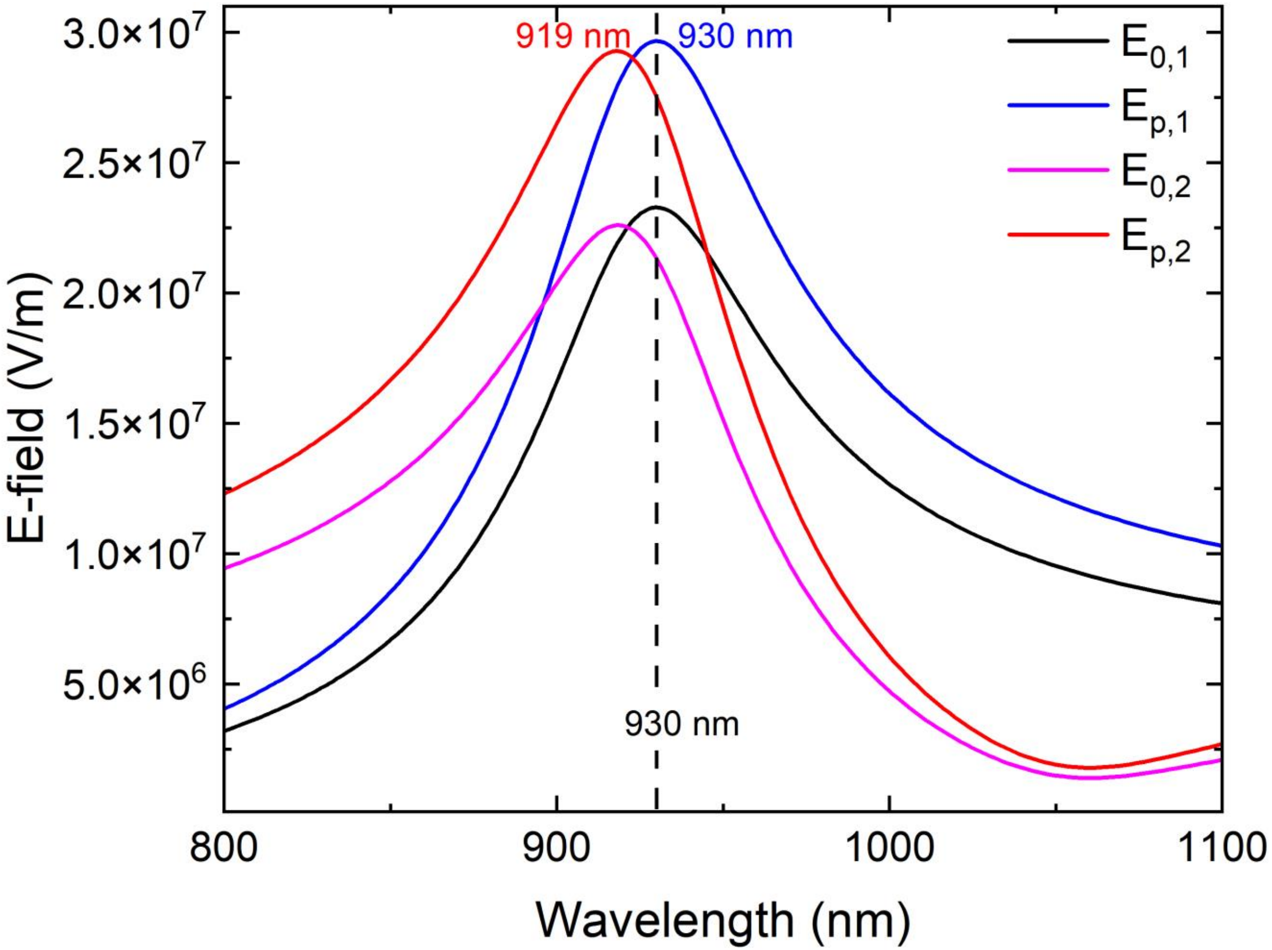






# Forces and *E*-fields



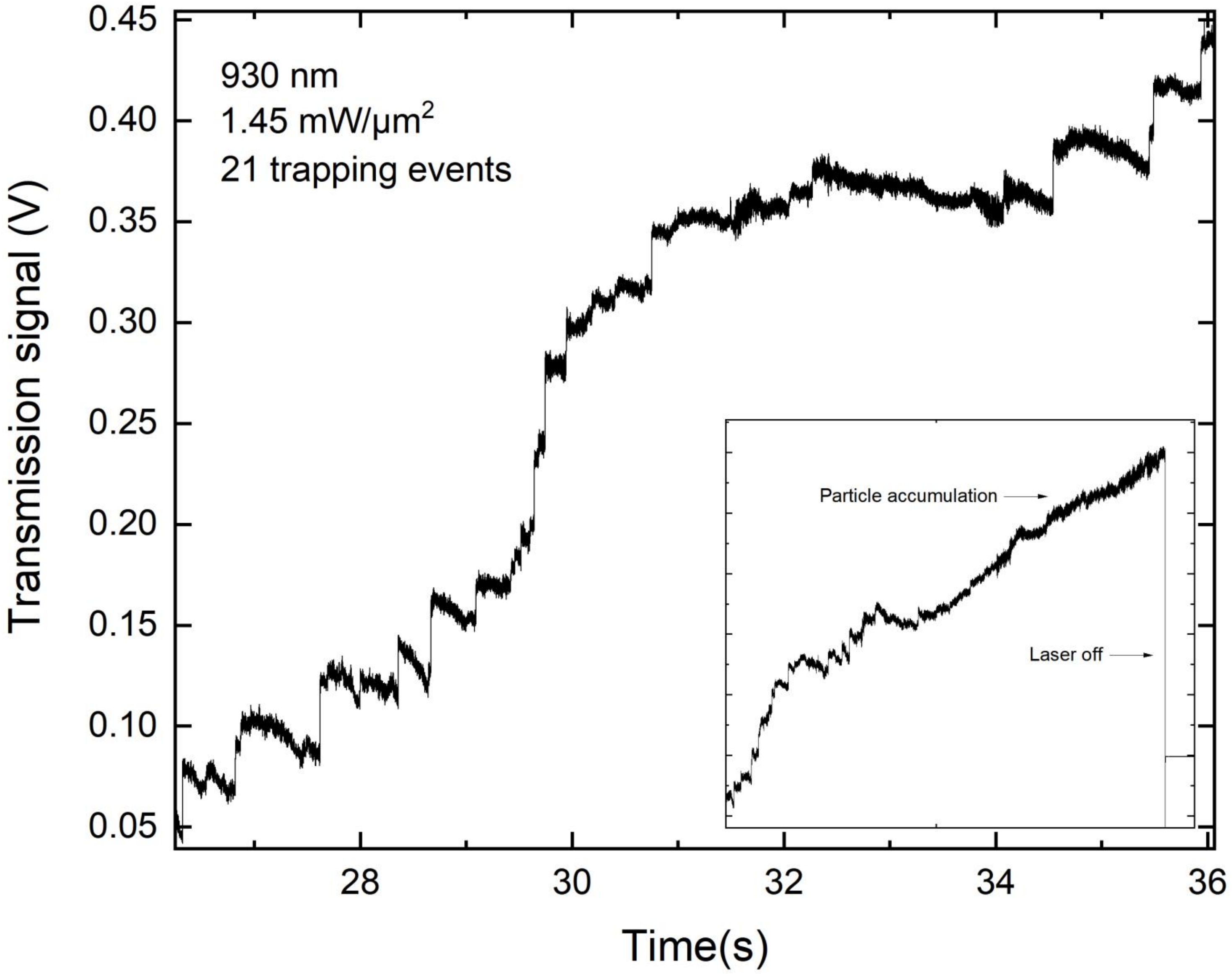


**Polystyrene particles at Hotspot 1 experience higher forces compared to particles at Hotspot 2**

# Experimental Results

**Solution**
0.2% v/v D7H
+ 0.1% v/v Tween-20 surfactant
in $D_2O$ (heavy water)

**Excitation laser**
930 nm wavelength
4.6 mW incident power



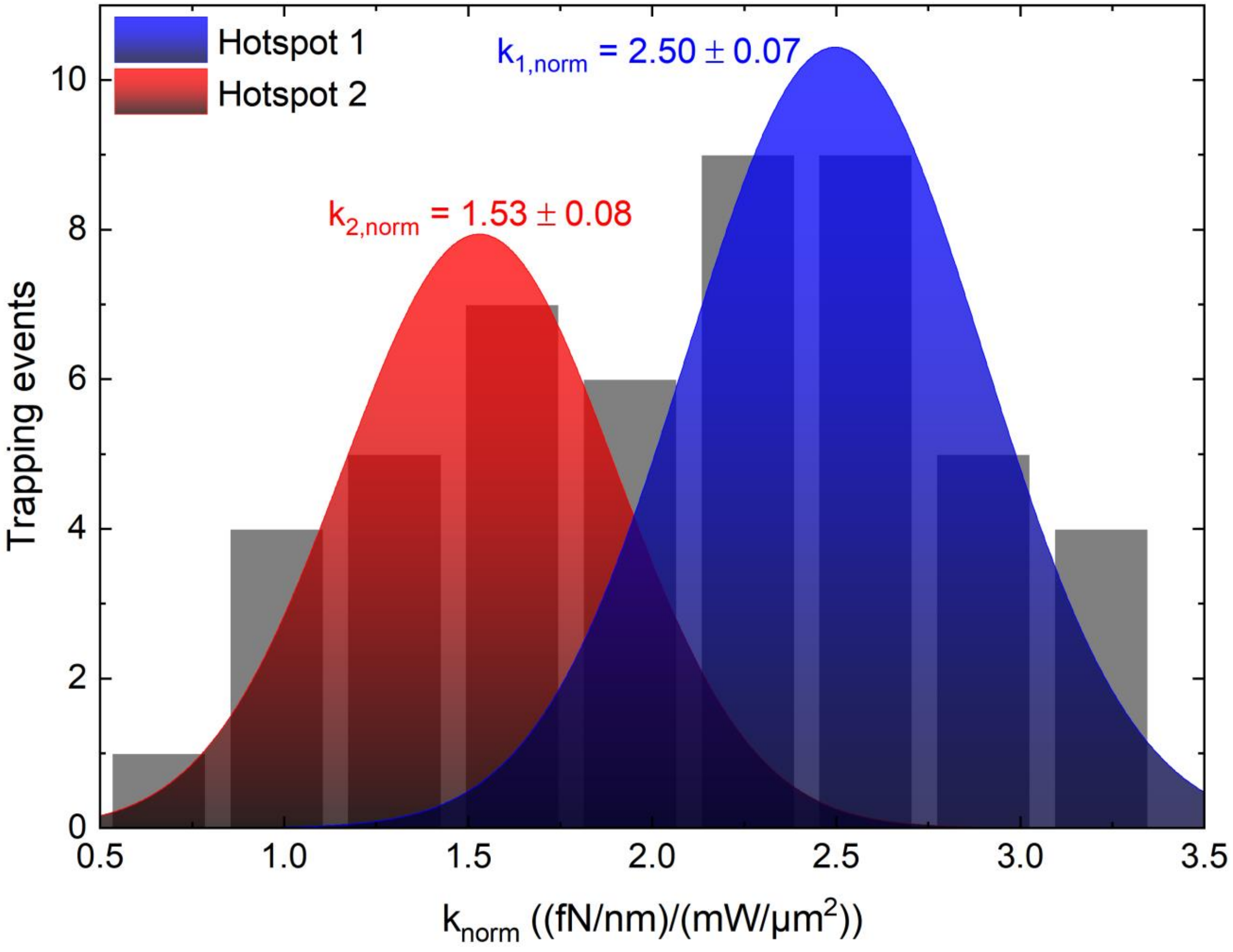
Occupancy

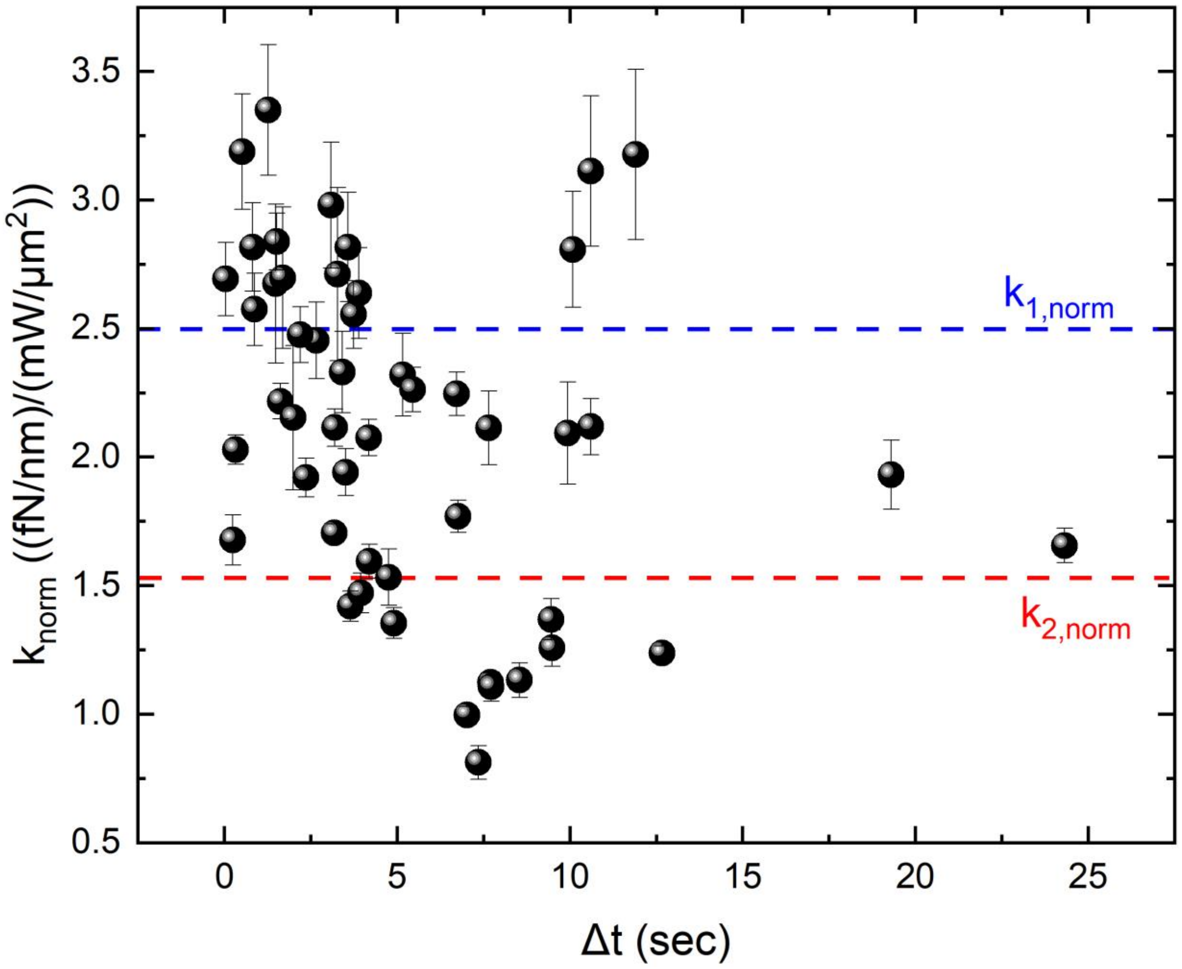
1st 28%

2nd 24%

3rd 15%

# Experimental Results





**Trapping events initially happen at the strongest hotspot (Hotspot 1)**

# Project Conclusion

✓ Metamaterial tweezers exhibit very high trap stiffness values on PS nanoparticles 20 nm in diameter, in good agreement with the simulations.

| | $k_{sim}$ (fN/nm)/(mW/$\mu$m$^2$) | $k_{exp}$ (fN/nm)/(mW/$\mu$m$^2$) |
|---|---|---|
| Hotspot 1 | 2.55 | $2.50 \pm 0.07$ |
| Hotspot 2 | 2.16 | $1.53 \pm 0.08$ |

✓ Ability of the design for fast, multiple nanoparticle trapping and positioning at the array's hotspots.

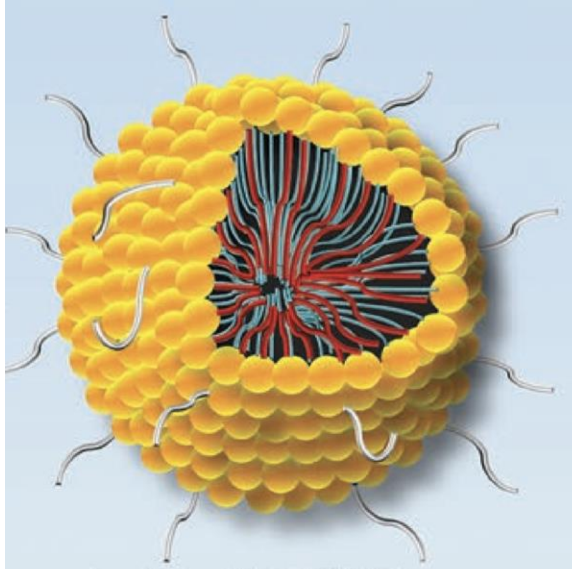
✓ Two types of hotspots on the metamaterial array, that can be tuned with the excitation wavelength and used for sorting applications.

✓ More than 10 sec of non-illumination is required in order for particles to be diffused away from the structures after trapping

# Contents

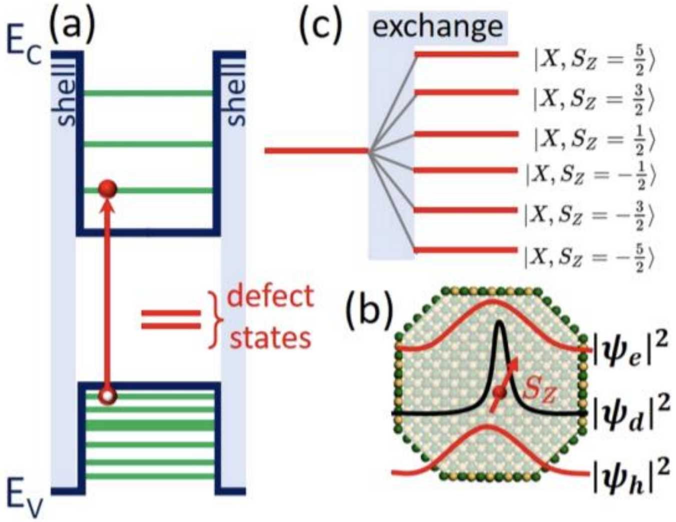
# 8) Trapping Quantum Dots

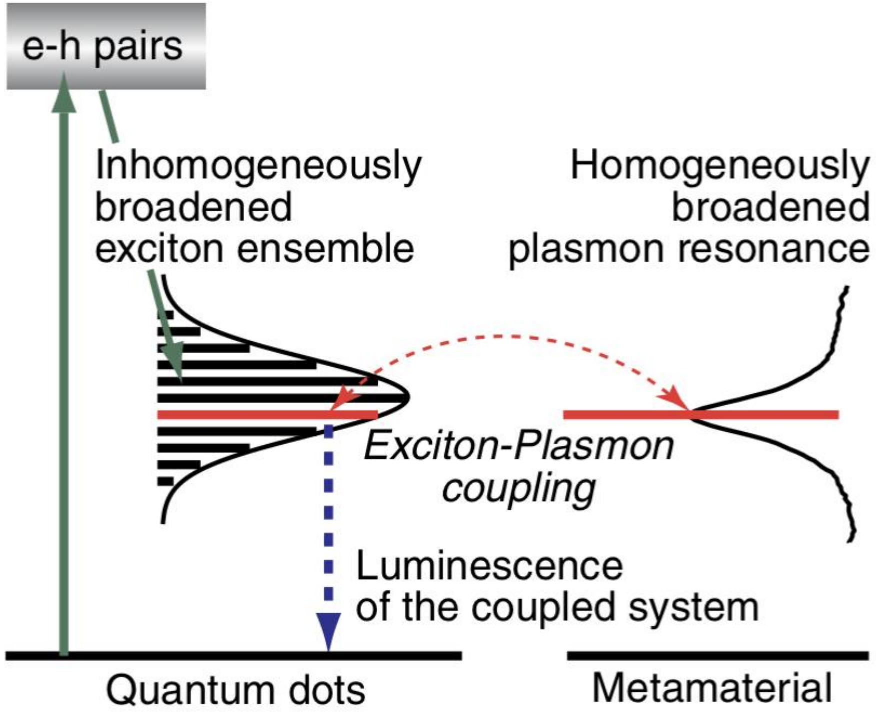
## Quantum Dots

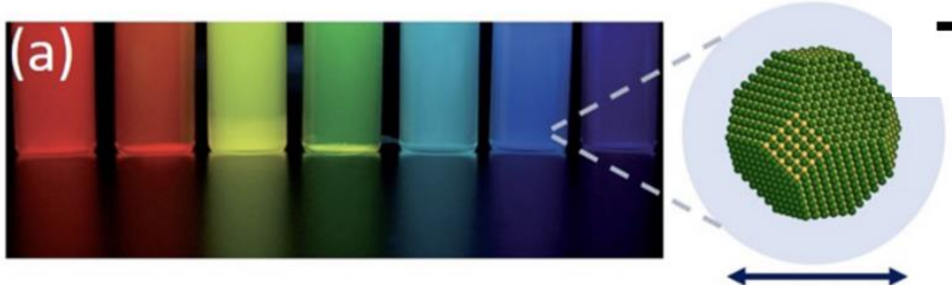


Core/shell

H. Zhao et al., Small 2021, 2105365







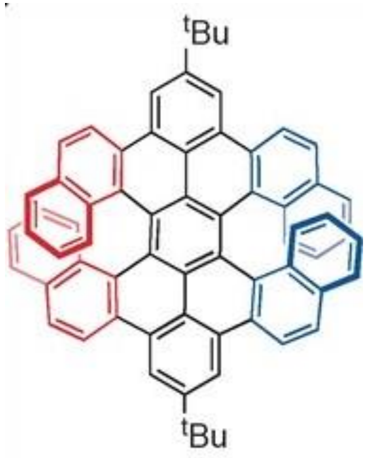
K. Tanaka et al., PRL, 2010, 105, 227430

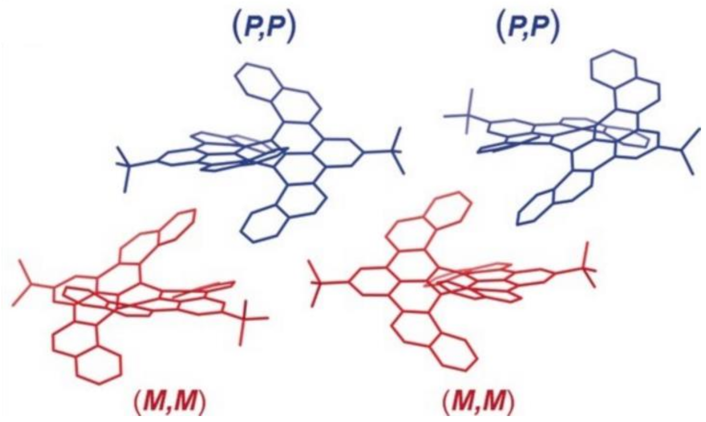
C.R. Kagan et al. Chem. Rev. 2021, 121, 3186–3233

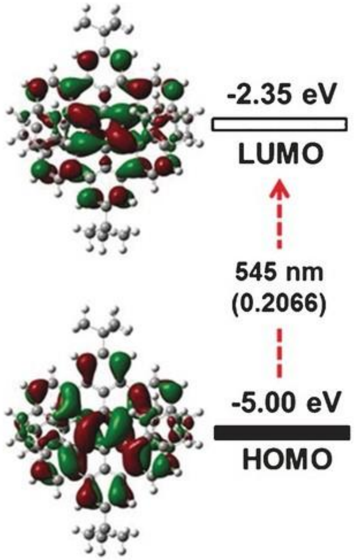
# 9) Trapping Quantum Dots

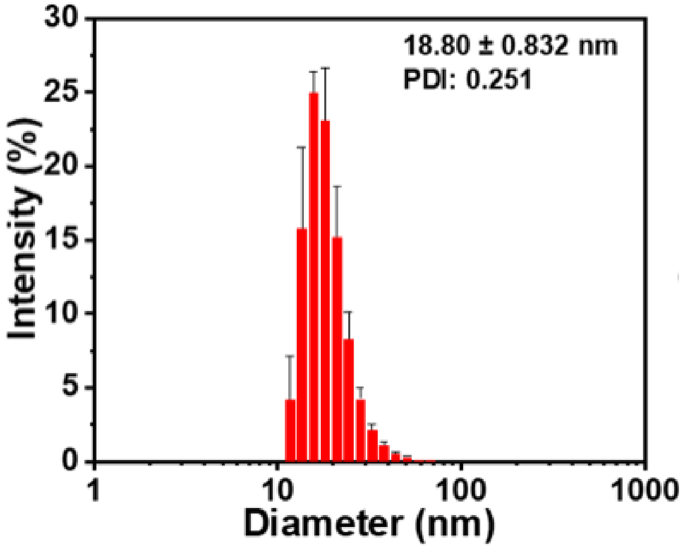
## Double–[7]–carbohelicene (D7H) QDs

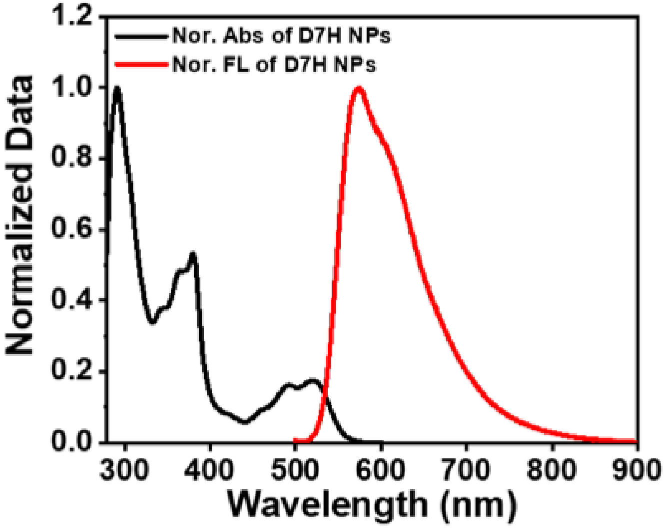
Y. Hu and A. Narita et al., Angew. Chemie Inter. Ed. 56, 3374–3378 (2017).

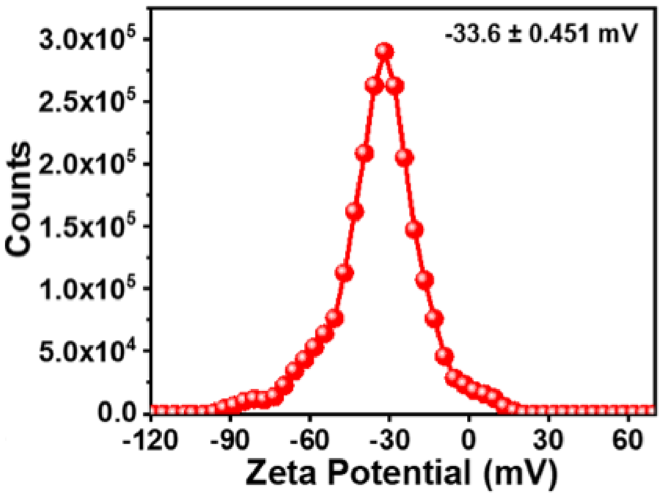












# Experimental Results

**Solution**

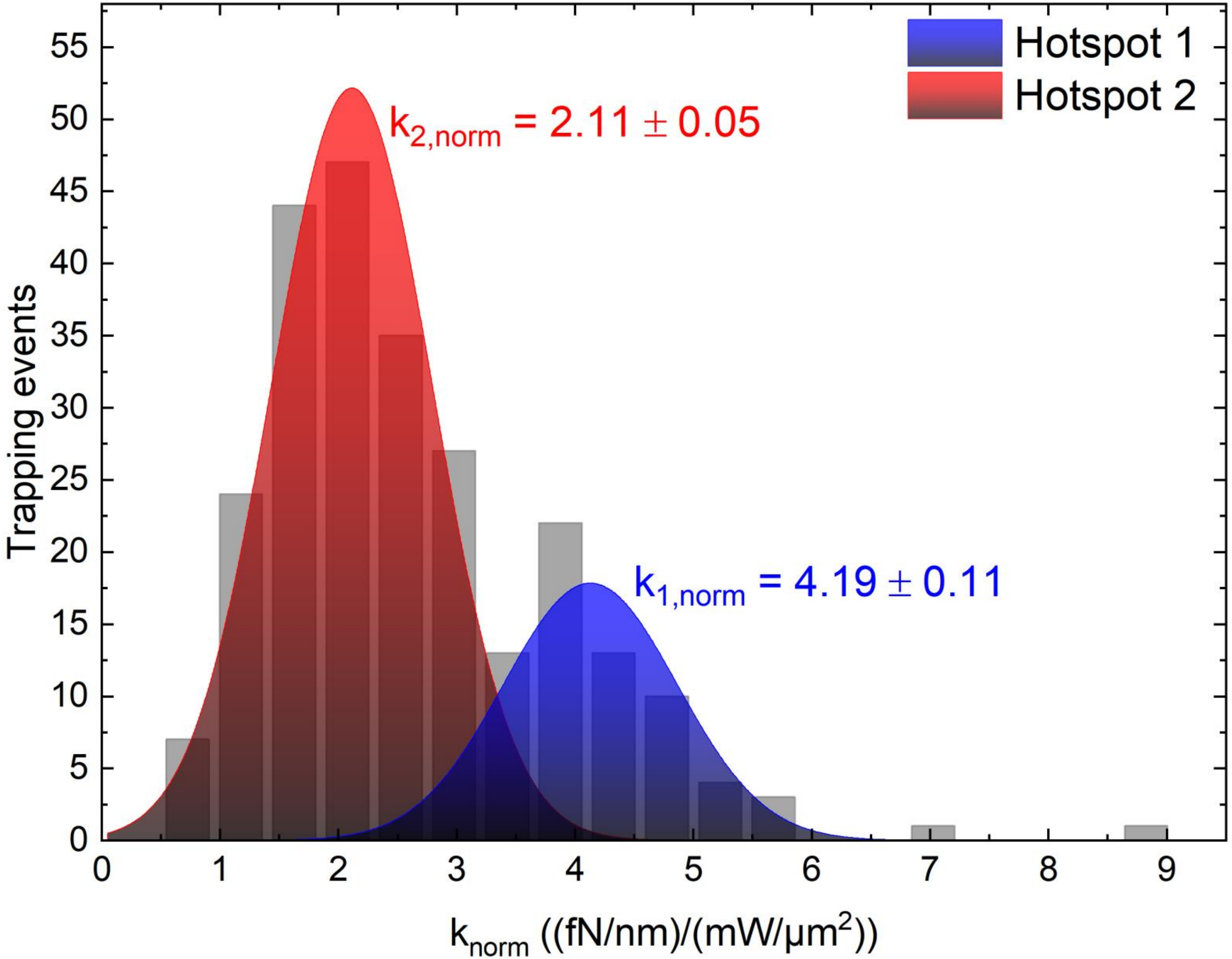
0.2% v/v D7H

+ 0.1% v/v Tween-20 surfactant in $D_2O$ (heavy water)

**Excitation laser**

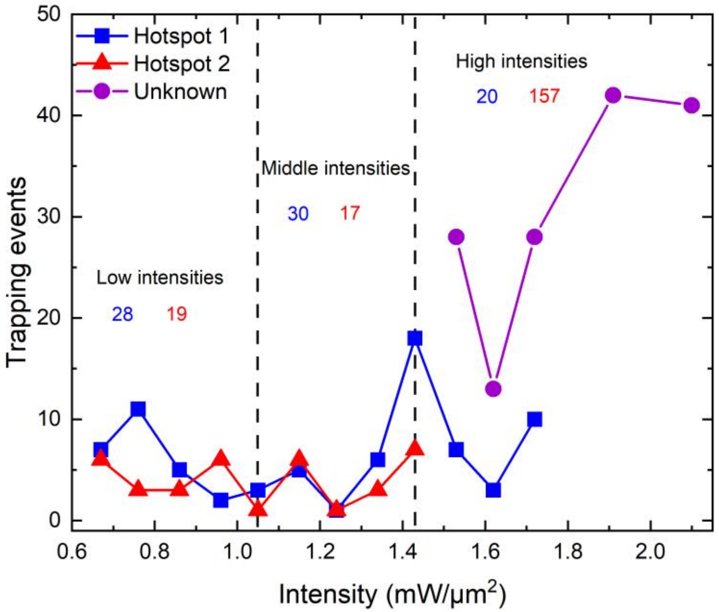
930 nm wavelength

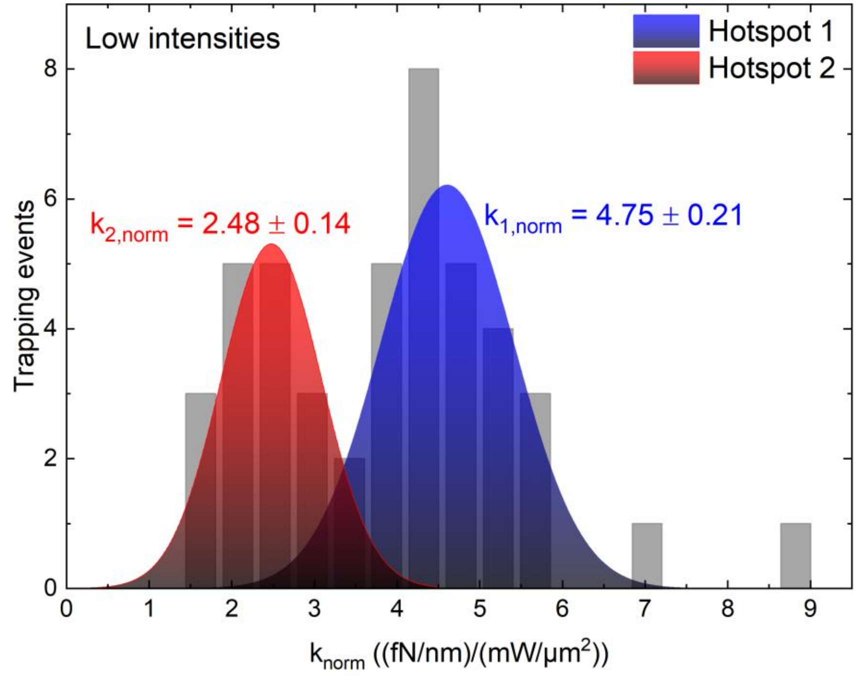
1.5 – 8.5 mW incident power

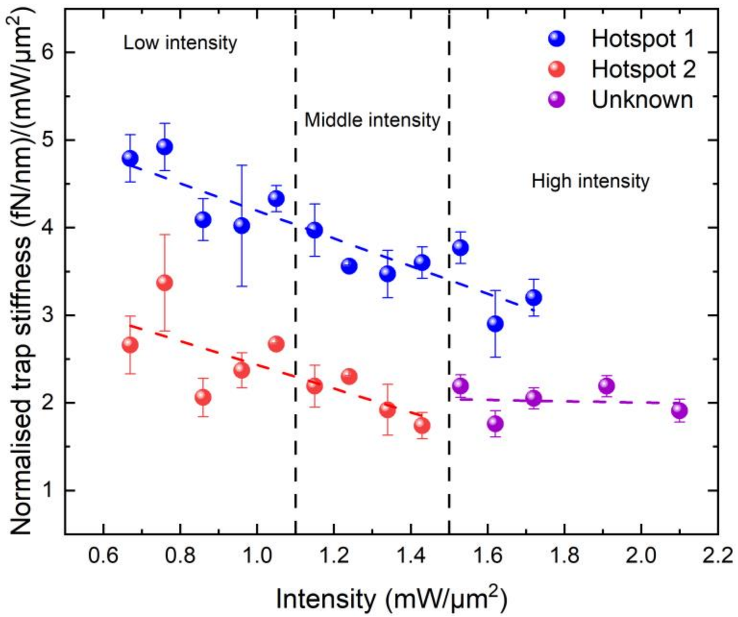


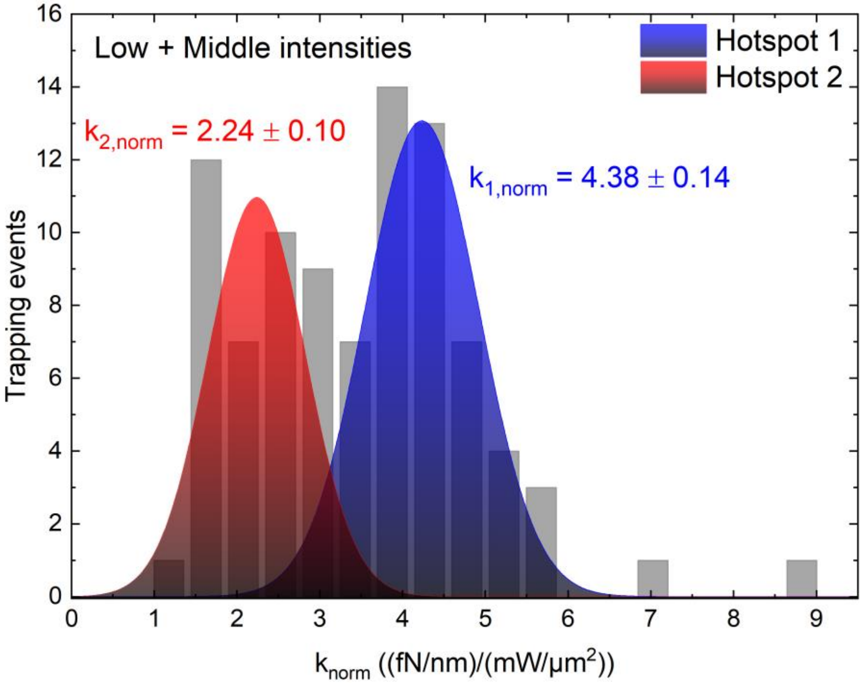
**More trapping events at Hotspot 2?**

# Experimental Results





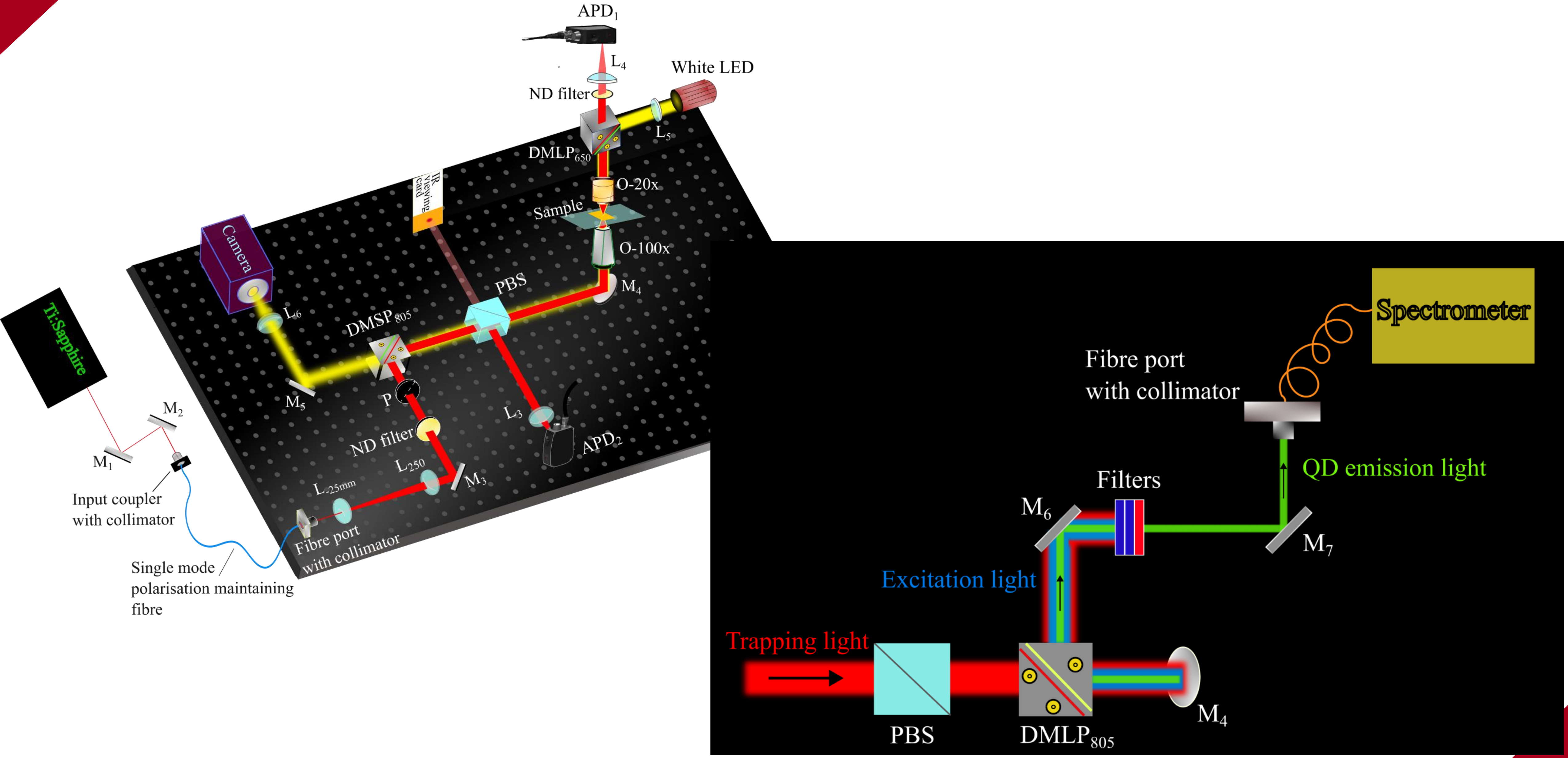




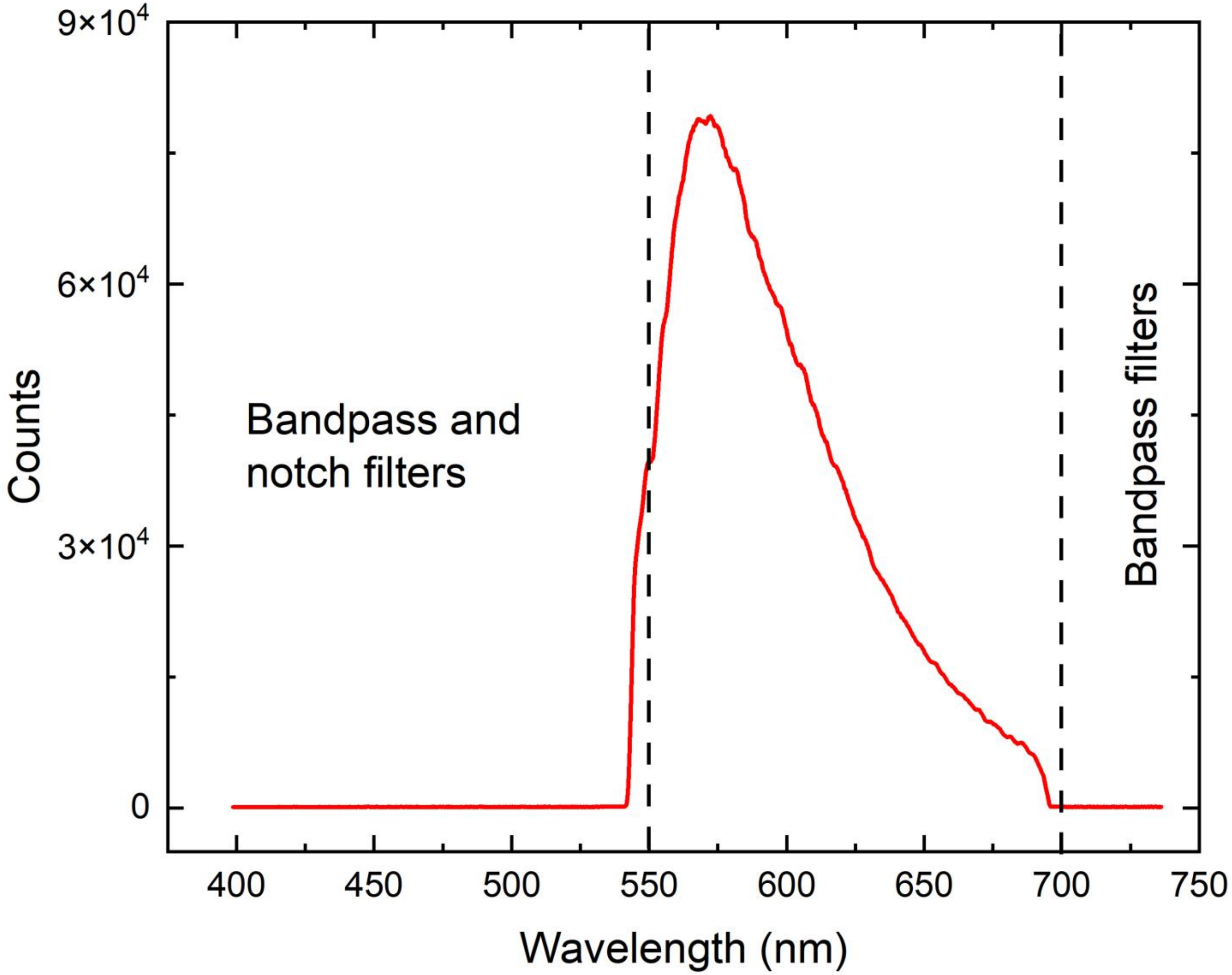
$$k_m = 2\frac{\alpha_d{}'}{c\varepsilon_0}\frac{I_0}{w_0^2}$$

$$-1.5\ k_{norm}/I_0$$

# Setup Modification



# D7H Photoluminescence



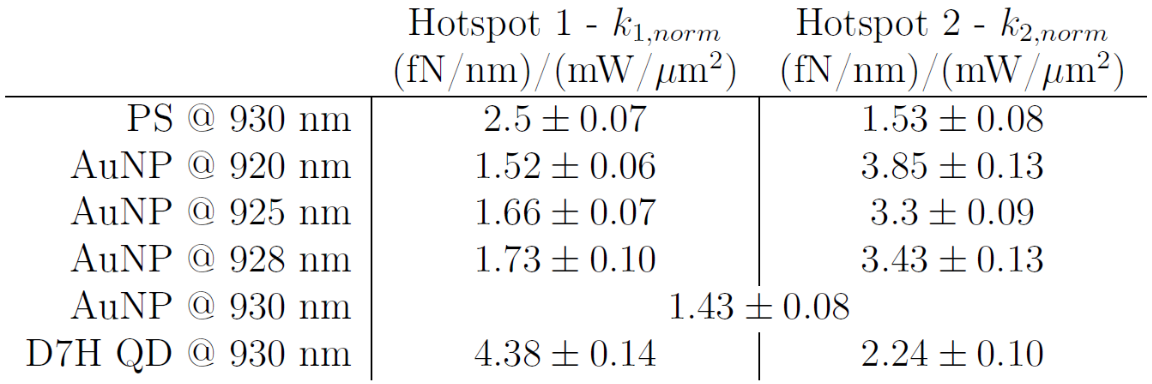
# Project Conclusion

- ✓ Trap stiffness as high as 8.8 (fN/nm)/(mW/μm$^2$)
- ✓ Explored trapping conditions of biocompatible D7H QDs and trapping intensity threshold
- ✓ Investigation of single-photon emission and PL enhancement due to Purcell effect?

# Conclusion and Future Perspectives

- ✓ Metamaterial plasmonic tweezers can be used for trapping a variety of nanoparticles such as PS, AuNP and QD, 20 nm in size or smaller, owing to the high sensitivity of the Fano interference.
- ✓ Very high trap stiffness values with extremely low trapping intensities.
- ✓ Ability for multiple particle trapping and nanopositioning on a periodic array.

- ➢ Obtain a better understanding of thermal effects and convection flows arising from laser illumination.
- ➢ Study the optical properties and interactions of the biocompatible D7H QDs for potential applications in quantum technologies and/or biomedical techniques.



| | Hotspot 1 - $k_{1,norm}$ $(\mathrm{fN/nm})/(\mathrm{mW}/\mu\mathrm{m}^2)$ | Hotspot 2 - $k_{2,norm}$ $(\mathrm{fN/nm})/(\mathrm{mW}/\mu\mathrm{m}^2)$ |
|---|---|---|
| PS @ 930 nm | $2.5 \pm 0.07$ | $1.53 \pm 0.08$ |
| AuNP @ 920 nm | $1.52 \pm 0.06$ | $3.85 \pm 0.13$ |
| AuNP @ 925 nm | $1.66 \pm 0.07$ | $3.3 \pm 0.09$ |
| AuNP @ 928 nm | $1.73 \pm 0.10$ | $3.43 \pm 0.13$ |
| AuNP @ 930 nm | $1.43 \pm 0.08$ | |
| D7H QD @ 930 nm | $4.38 \pm 0.14$ | $2.24 \pm 0.10$ |

# List of Publications

1) T. D. Bouloumis, D. G. Kotsifaki, and S. N. Chormaic, Enabling self-induced back-action trapping of gold nanoparticles in metamaterial plasmonic tweezers, Optics (physics.optics), arXiv:2211.08613, (2022).

2) 2) T. Bouloumis, D. G. Kotsifaki, X. Han, S. Nic Chormaic, and V. G. Truong, Fast and efficient nanoparticle trapping using plasmonic connected nanoring apertures, Nan- otechnology, 32, 025507, (2020).

3) 3) T. D. Bouloumis and S. Nic Chormaic, From far-field to near-field micro- and nanopar- ticle optical trapping, Applied Sciences, 10, 4, 1375, (2020).

Theodoros.Bouloumis@oist.jp

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- Scientific Computing and Data Analysis section
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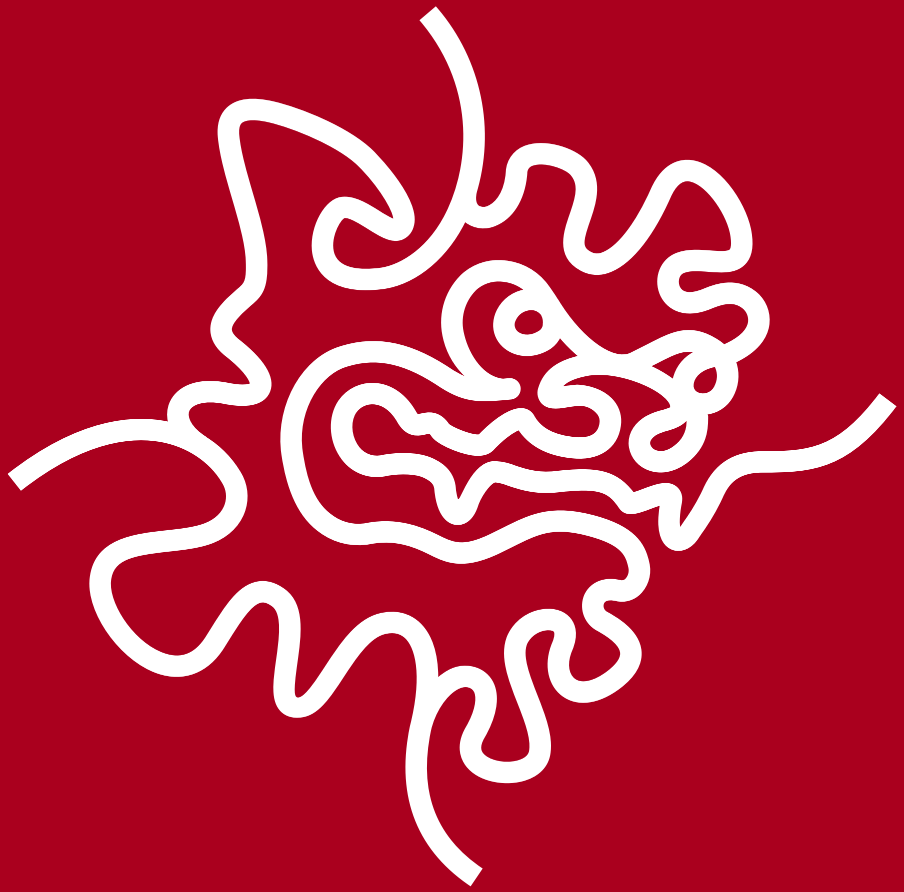

# Thank you!