Whispering gallery mode in super-resolution microsphere-assisted microscopy

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Abstract

In classical microscopy, the diffraction of the light limits the resolving power of the system. Observation of nanoscale elements through an optical microscope appears often to be restricted. From the cut-off frequency of the optical transfer function, the lateral resolution of an optical microscope can thus be quantified as 0.5 Lambda/NA, where Lambda and NA are the wavelength of the light source and the numerical aperture of the microscope objective, respectively. A white-light microscope thus allows the visualisation of objects having a minimum size that is just greater than half of the wavelength of the illumination in air. Recently, several far-field methods have been developed in order to overcome this limitation. Microsphere-assisted microscopy is a modern technique which allows the diffraction limit to be broken. In 2011, Wang *et al.* developed two-dimensional super-resolution imaging through glass microspheres. They showed that microsphere-assisted microscopy distinguishes itself from others by being able to perform label-free and full-field acquisitions. In addition, with only slight modifications of classical white-light microscopy, microsphere-assisted microscopy makes it possible to reach a lateral resolution of a few hundred nanometres (~$\lambda/7$ in immersion). Placing a microsphere on a sample, directly or at a few hundreds of nanometres distance allows the generation of a super-resolved virtual image of the object which is then collected by a microscope objective. Currently several studies have been aimed at providing a better understanding of the super-resolution phenomenon in microsphere imaging. Now we know that the performance in microsphere-assisted microscopy depends on the optical and geometrical parameters. According to many studies on the PJ prediction, the imaging process in microsphere-assisted microscopy can be addressed by considering the sphere as a *photonic jet lens*. However, recently, we demonstrated that the photonic jet (PJ) generation by a microsphere, and considered here as the point spread function, is not small enough to justify this resolution improvement in the imaging process. Although the size of the focus spot overcomes the diffraction limit, the full width at half maximum of the PJ waist is around a third of the wavelength, which is lower than the super-resolving power which is around $\lambda/7$ in immersion. However, the PJ phenomenon can explain the imaging through the microsphere, the nature of the image, the position of the image plane and the lateral magnification dependence provided by the microsphere. Moreover, we have investigated the contrast in the virtual image according to the relative phase difference between close point sources. When the point sources are initially in-phase, the two virtual images cannot be distinguished. However, when the point sources are initially out-of-phase, the two virtual images can be clearly distinguished. Our work considers a third hypothesis by contributing to the investigation of the role of whispering gallery modes (a radially evanescent wave) in the microsphere assisted microscopy mechanism through numerical simulations using a finite element method.

Evanescent waves in super-resolution microsphere-assisted microscopy

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Introduction

Classical microscopy : limited by diffraction (~ 200 nm, visible)

- In 1873, Ernst Abbe :

$$R = \kappa \frac{\lambda}{NA}$$

- PSF, MTF…

- *The resolution limit formula engraved in an Ernst Abbe memorial in Jena*
- *Foundation of Optics and mechanics of precision Institute in Sétif (Zeiss company, 1979)*

Enhancement of the resolution

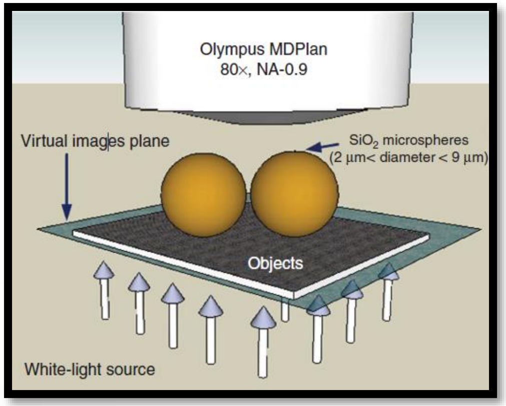
- Reducing the wavelength
- Increasing the numerical aperture
- Increasing the refractive index (immersion objectives…)

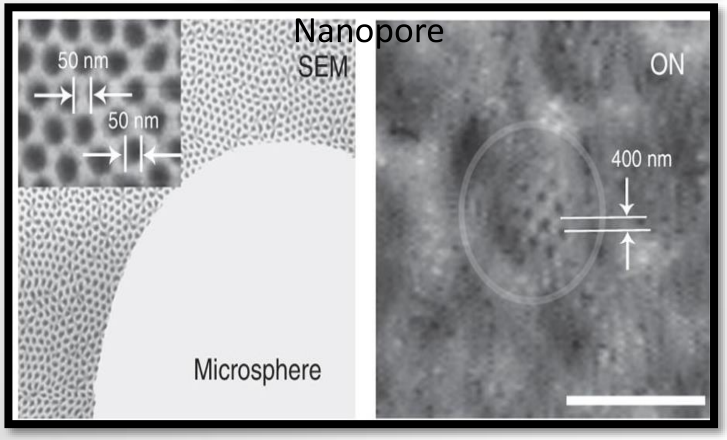
1. Super-resolution µ-sphere assisted microscopy

2011: Experimental demonstration in 2D

- **Imaging through a microsphere** (n = 1,46, D ~ 2-9 µm)
- **White light illumination**
- **Nanopore observation of 50 nm in air**

Principle

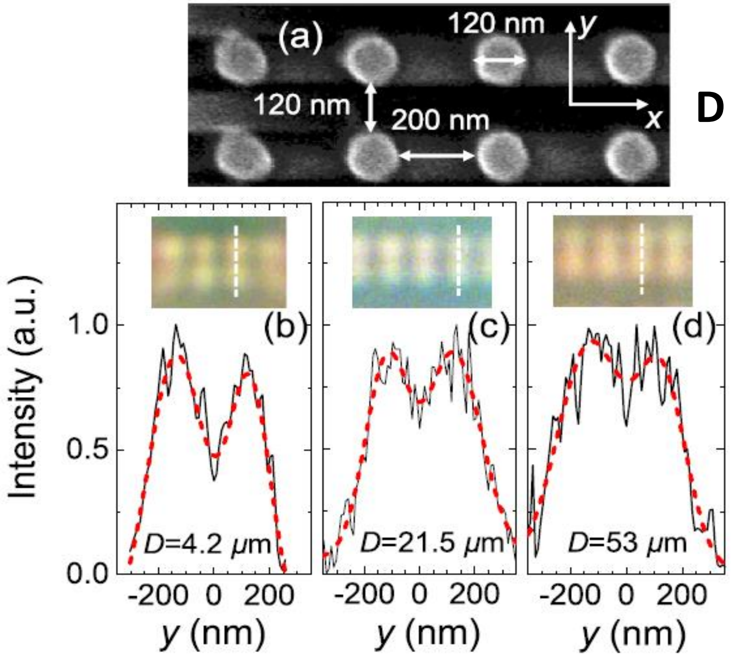




Wang *et al.*, Nat. Commun. 2, 218 (2011)

2012: in immersion with barium titanate glass microsphere (n = 1.9)

- **Imaging through a microsphere**
- **Resolution = λ_0 / 7 (λ_0 = 800 nm)**



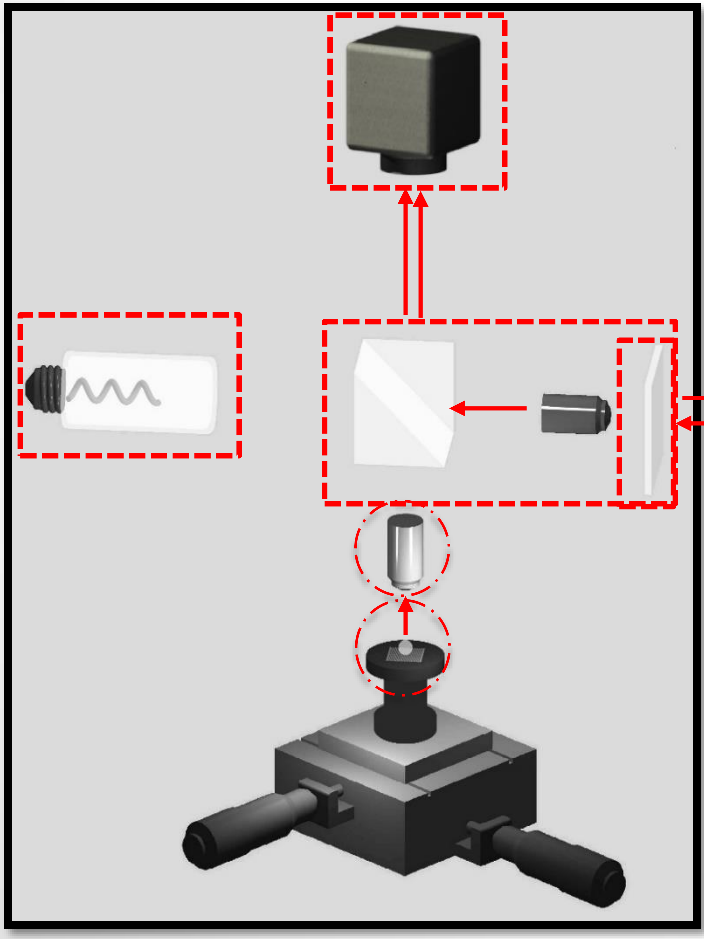
D = 4 µm, 21 µm and 53 µm in water

Estimation of the resolution → PSF

Darafsheh *et al.*, Appl. Phys. Lett. 101, 141128 (2012)

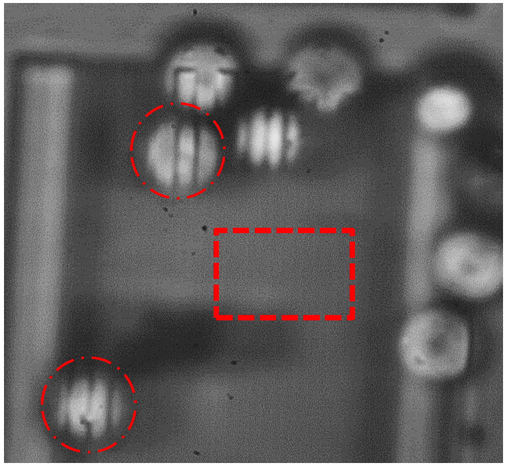
2. Interferometric configuration (Setup)

Imaging phase

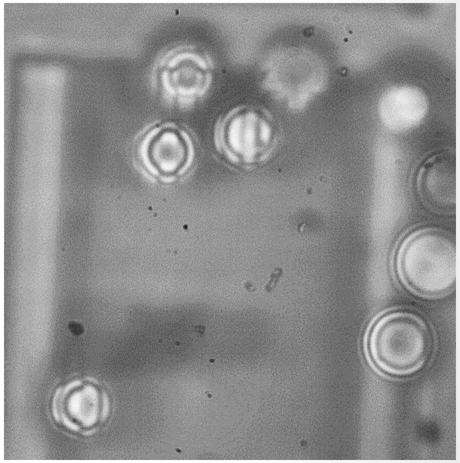


Linnik configuration in white light with 50x objectives (ON = 0.85)

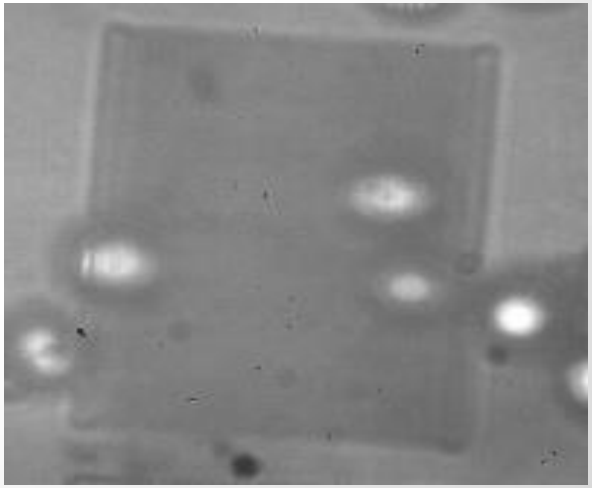
Linnik without fringes



Linnik with fringes

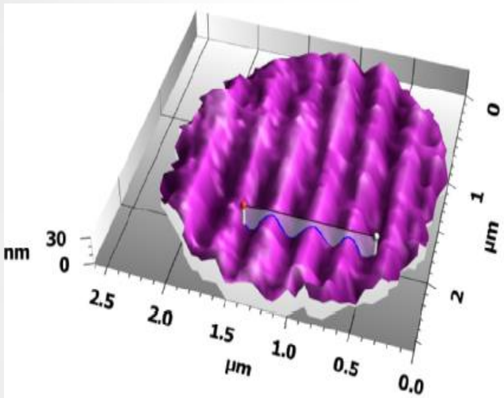


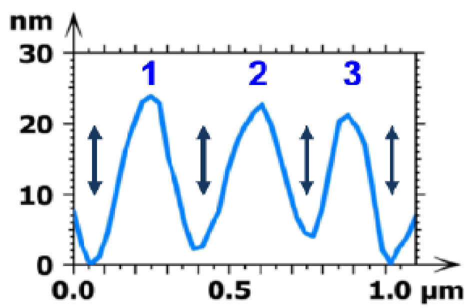
Resolution standard: gratings with a period of 3 µm



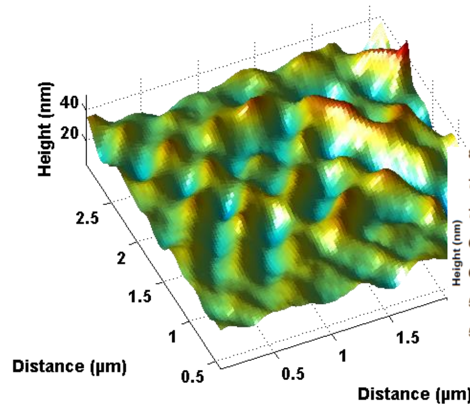
2. Interferometric configuration (Results)

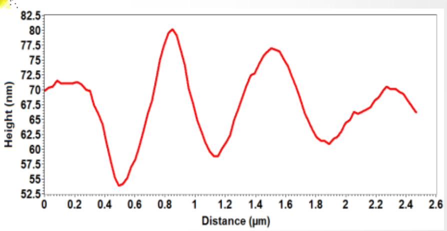
In Mirau configuration





In Linnik configuration





Polymer spheres , Ø = 11 µm (n = 1.68)

λ_0 = 600 nm, x50 (ON = 0.55), in air

<u>Blu-Ray : period of 300 nm</u>, height of ~22 nm

[Kassamakov, Lecler et al. Scientific Reports 7, 3683, 2017]

Glass Sphere Ø = 24 µm (n = 1.5)

λ_0 = 600 nm, x50 (ON = 0.3),

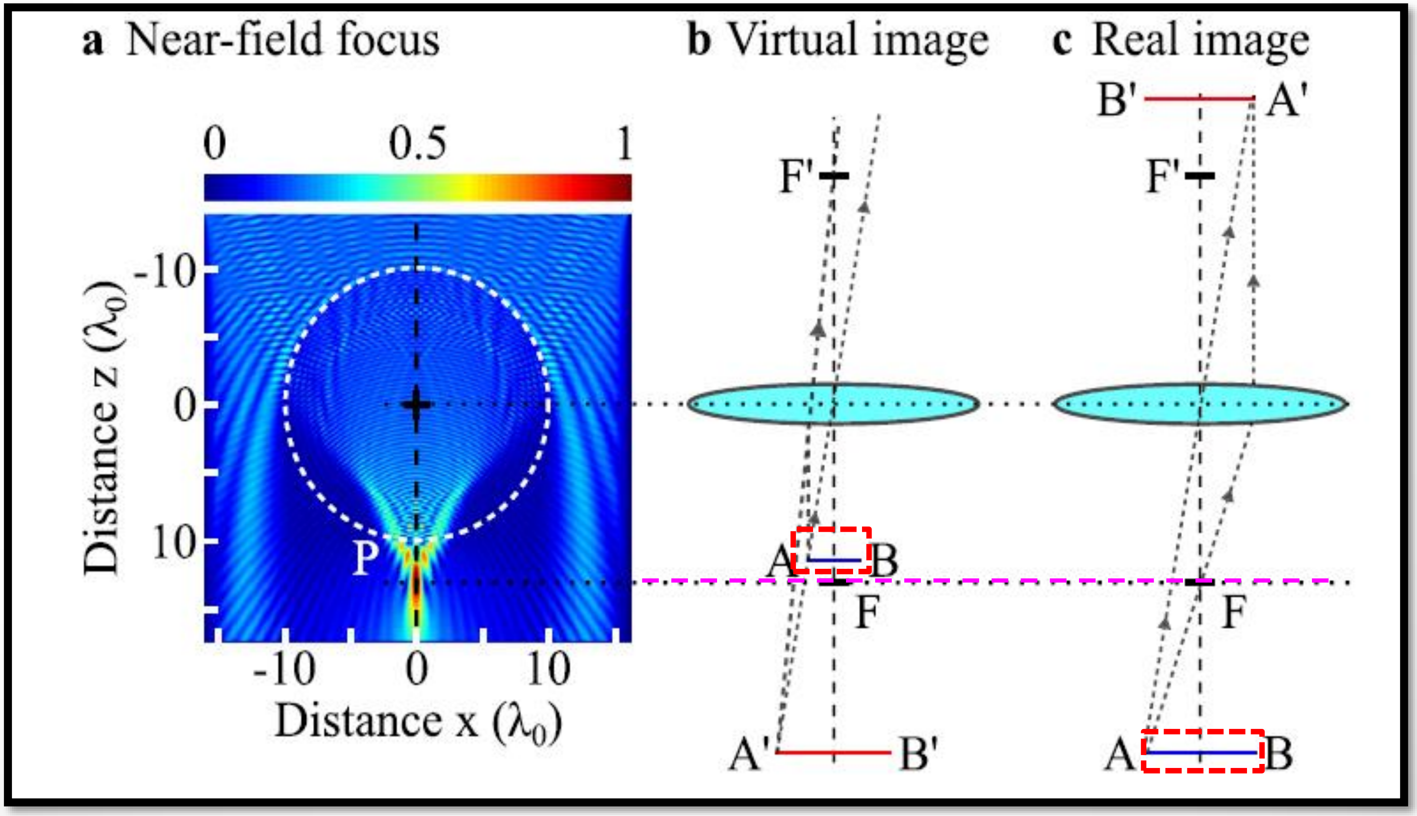
<u>Ag Nano-dots : Ø = 200 nm</u>, height 20 nm

[S. Perrin et al., Applied Optics 56 (2017)]

3D profile, topography and volume reconstruction

3. Photonic jet :

Mechanism of imaging

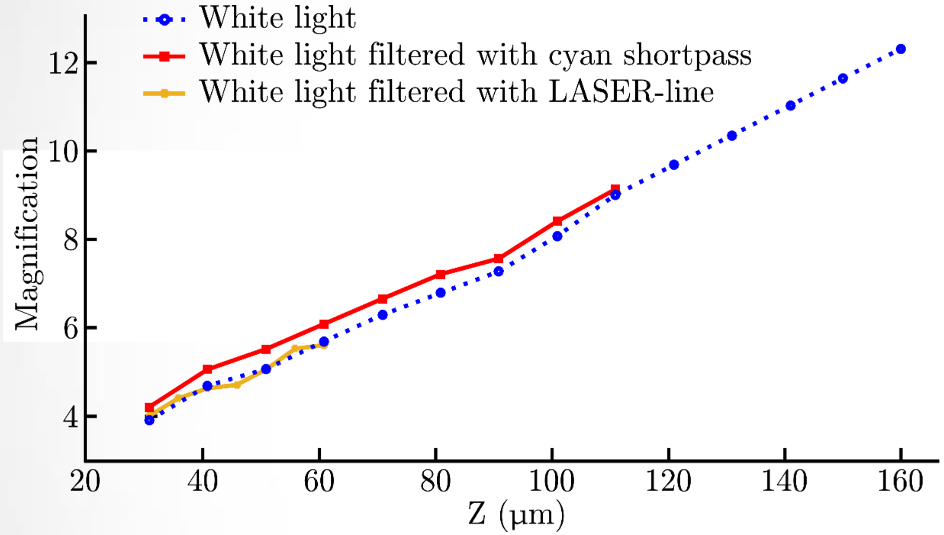


PNJ gives the focal point of the microsphereas a lens

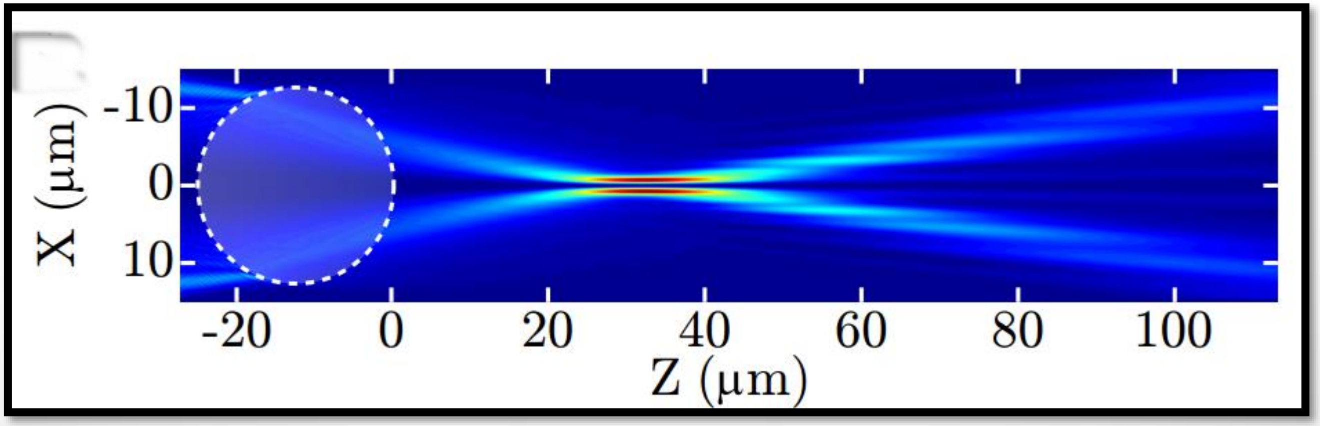
Sum Sam Lai *et al.*, PLoS ONE 11, e0165194 (2016)
Lecler, Perrin *et al.*, Sci. Rep. 9, 4725 (2019)
Maslov, Astratov, Phys. Rev. Appl. 11, 064004 (2019)

FWHM Photonic jet = λ / 3
whereas FWHM PSF > λ / 4

4. Unconventional magnification



- The magnification changes along the sphere imaging depth
  - 25 µm glass µ-sphere



- Virtual image simulation of two point sources, white light (Δλ =400 nm)

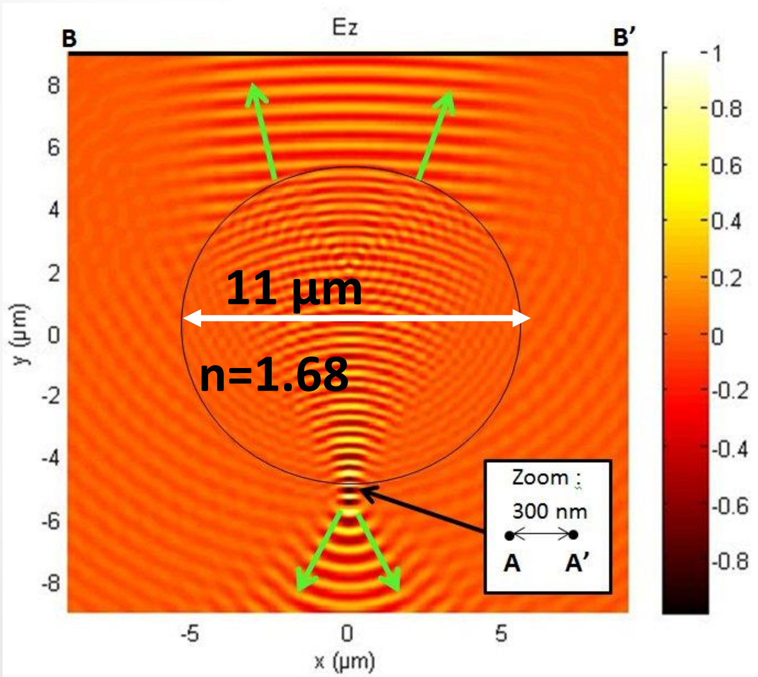
Perrin *et al.*, Opt and Laser Tech. 40-43, 114 (2019)

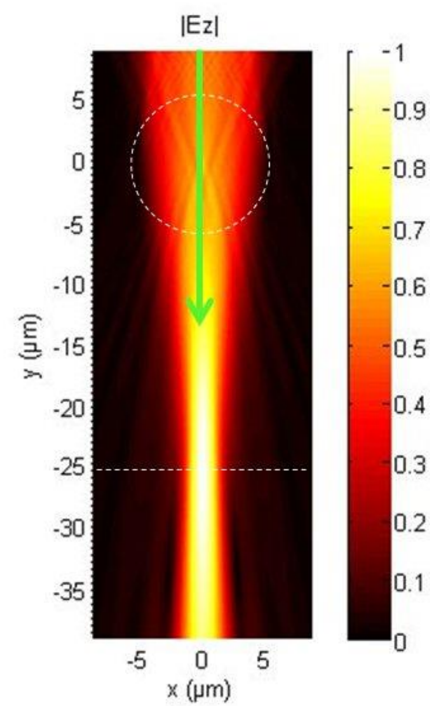
5. Role of coherence in the resolution

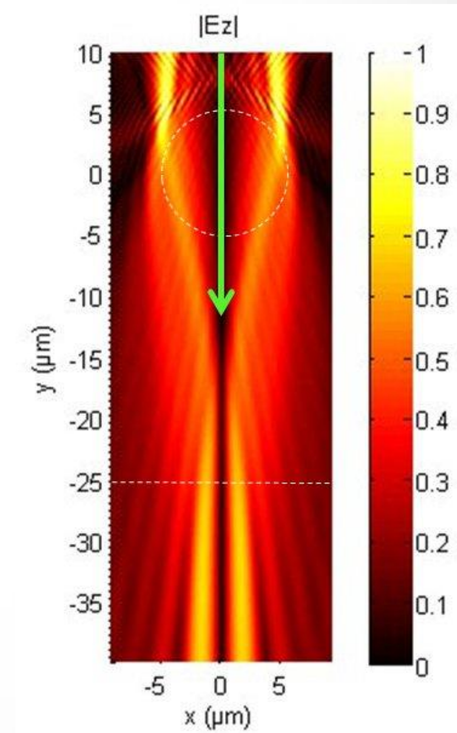
Direct propagation produced by two point sources separated by 300 nm

Time-reversal propagation

in-phase sources **Out-of-phase sources**







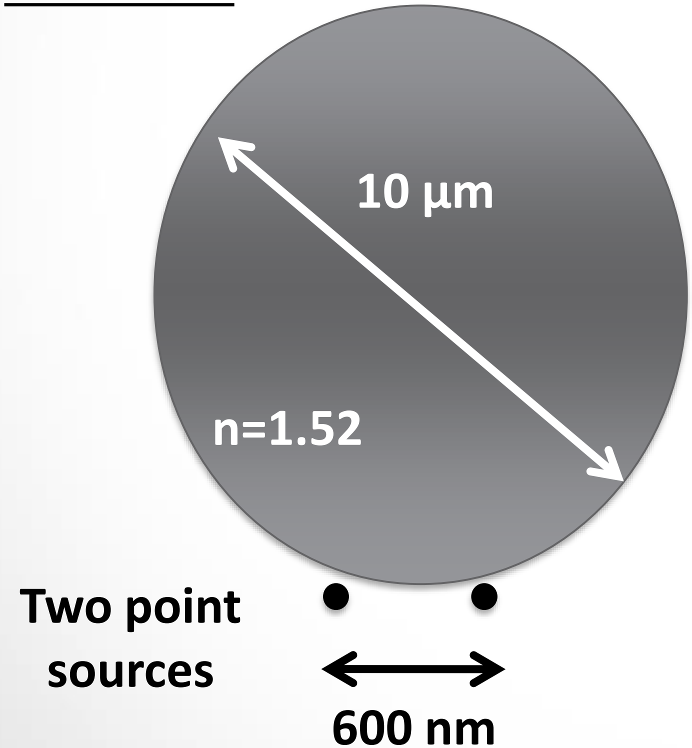
- **The coherence of the illumination source has an important role in the super resolution**

Kassamakov, Lecler *et al.*, Sci. Rep.7, 3683 (2017)

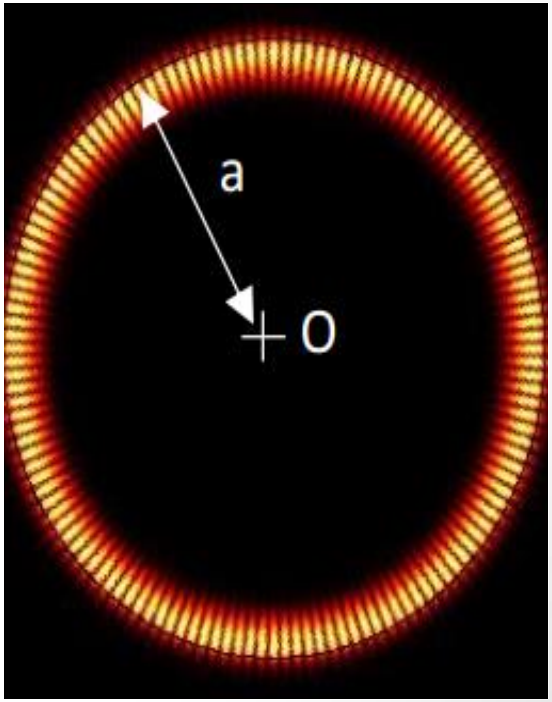
6. Effect of Whispering Gallery Modes

Simulation: WGM natural excitation in a 10 µm-diameter sphere with n=1.52
wavelength = 625 nm

- **Excitation :**



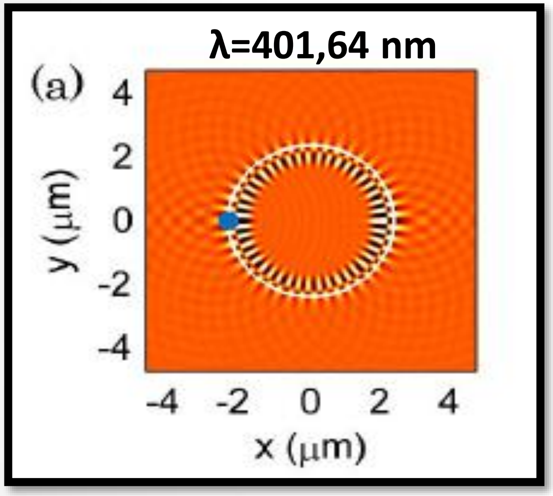
- **Results :**



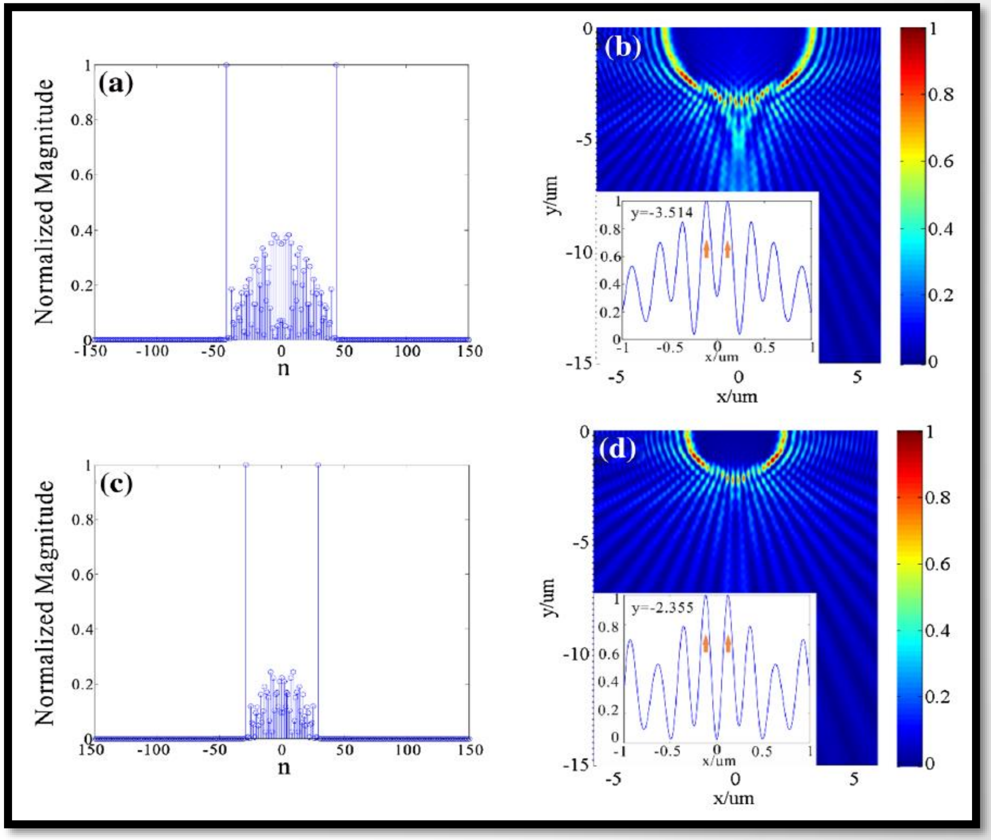
WGM resonance at λ = 625 nm

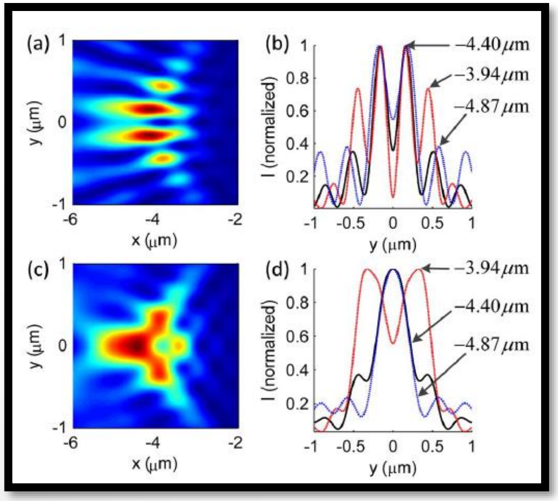
💡 **Point source near µ-sphere can excite WGM resonance**

6. Effects of Whispering Gallery Modes



- **The high-order mode plays a dominant role in imaging when WGM excitation is present.**



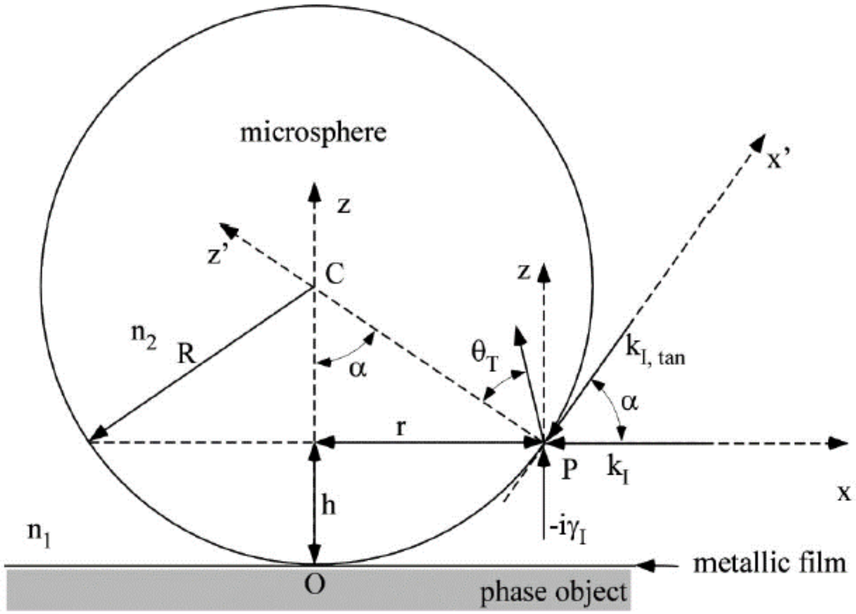


- **Whispering gallery modes WGM increase the resolution up to λ/4**

Duan *et al*., Opt. Lett. 38, pp. 2988-2990 (2013)
S. Zhou et al., Appl. Phys. B. 123:236 (2017)

7. Contribution of evanescent waves

Conversion of evanescent waves (high frequencies) into propagating waves by the microsphere.



Snell-Descartes law can be applied with evanescent waves

Enhancement of resolution using microspheres

BEN-ARYEH, JOSA 33, 2284 (2016)

Conclusion

- **Light focused beyond diffraction at the <u>meso-scale</u>**
  - ➢ **Photonic jet behaves as the focus point of the microsphere**
- **Optical, label free, full field <u>2D super-resolution </u>(λ/7~ 50 nm)**
  - ➢ **Role of coherence has an important role in the super resolution.**
  - ➢ **Evanescent waves (with WGM) seem to play a key role in super-resolution**
- **Measuring phase: possibilities of 3D reconstruction and topography**
  - ➢ **3D more isotropic spacial resolution**

Thank you for your attention!

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