

Evanescent waves filtering in microsphere assisted microscopy imaging

Boudoukha Rayenne
*ICube Research Institute,
 Université de Strasbourg
 Strasbourg, France*

ORCID: 0000-0001-9803-9218

Demagh Nacer-E.
*Institute of Optics and Precision
 Mechanics,
 Ferhat Abbas University
 Setif, Algeria*
 ndemagh@univ-setif.dz

Perrin Stéphane
*Photonics Bretagne,
 Lannion, France*
 sperrin@photonics-bretagne.com

Montgomery Paul
*ICube Research Institute,
 Université de Strasbourg-CNRS
 Strasbourg, France*
 paul.montgomery@unistra.fr

Guessoum Assia
*Laboratoire d'Electronique Quantique,
 Faculté de physique, USTHB,
 Alger, Algeria*
 assiademagh@yahoo.fr

Lecler Sylvain
*ICube Research Institute,
 INSA Strasbourg
 Strasbourg, France*
 sylvain.lecler@insa-strasbourg.fr

Abstract—Microsphere assisted microscopy is a label free, full-field, super-resolved technique, where a microsphere is used as an additional lens under a microscope objective and in the near field of the sample. We show how in the imaging process, the contribution of the evanescent waves is very selective and how the microsphere behaves as a filter. The demonstration is achieved by 2D-finite element simulation and using the recently introduced evanescent point source concept.

Keywords—*microscopy, microsphere, super-resolution, evanescent waves, near-field effect, evanescent point source*

I. INTRODUCTION

In microscopy, the resolution increase is a long-term history. Since Abbe and up to the end of the 20th century, the limit was considered to be the diffraction limit. To be distinguished at least a half wavelength may separate two objects [1]. Since many techniques have been developed to reach higher resolutions. We talk about super-resolution microscopy. Among all these techniques, we can cite the scanning near-field optical microscopy [2], solid immersion lenses [3] superlenses [4] and PALM/STORM techniques [5, 6]. However, these techniques are not necessarily easy to implement. In comparison, Micro-sphere Assisted Microscopy (MAM) is a full-field label free technique [7]. With this technique a glass microsphere in contact with the sample or at a distance smaller than 1 μm is used as a microlens; a resolution of $\lambda/5$ in air and $\lambda/7$ in immersion can be reached [8-14]. The physical explanation of this resolution has progressed but is still considered as an open question. A rigorous electromagnetic simulation of light interaction with the microsphere is required [15-18], especially to take into account the evanescent waves [19-20].

Recently, we have proposed the concept of “evanescent point source” in simulation to help to understand [21]. Namely, in the electromagnetic wave emitted by a classical point source, as a Hertzian dipole, the propagative part and the evanescent part cannot be distinguished. They are intrinsically linked. The evanescent point source makes it possible to have a localized electromagnetic peak amplitude made of only evanescent waves. In this study, we show how in the imaging process of these evanescent waves by a glass micro-sphere, the sphere acts not only as a microlens but behaves as a filter.

II. METHOD

Two evanescent point sources out of phase will be used as objects for a 2D TE finite-element simulation to study their imaging by a microsphere. Fig.1a illustrates the electric field along the X-axis (sample axis) of these points sources. The wavelength is supposed to be $\lambda = 600$ nm in air. The two electric field peaks are separated by $d = 200$ nm, that is smaller than a half-wavelength. The evanescence nature of the waves is in the Y-direction and is therefore not visible in this figure. Fig.1b illustrates the corresponding Fourier transform. For each k_x spatial frequency corresponds an equivalent wave propagating in air in the x direction. If $k_x > k_0$ with $k_0 = 2\pi/\lambda$ the wave is evanescent in the Y-direction (due to $|\mathbf{k}| = 2\pi/\lambda$ in air).

The generation of these waves, evanescent in the Y-direction is described in Fig.2. They are generated by total internal reflection of plane waves at the interface between a substrate of refractive index n_{sub} and the ambient space with $n_{\text{amb}} = 1$. The substrate does not need to correspond to a real material. Here, $n_{\text{sub}} = 10$ has been chosen to reach evanescent waves with enough high k_x spatial frequencies.

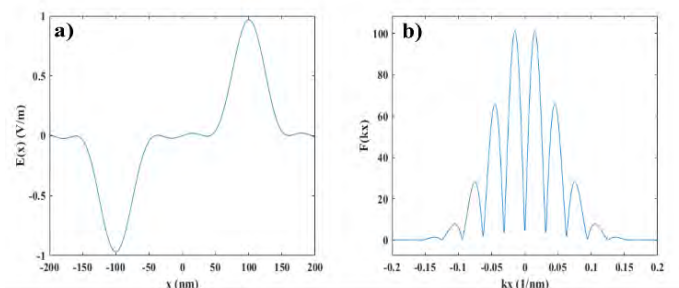


Fig.1 (a) Electric field of two evanescent point sources out of phase separated by $d = 200$ nm. $\lambda = 600$ nm. (b) Corresponding Fourier transform.

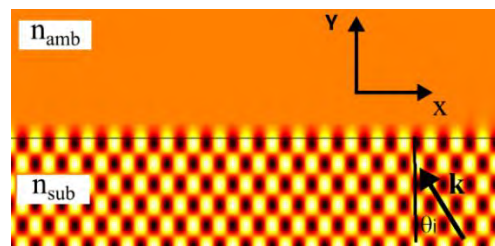


Fig.2 Generation of a wave in air, evanescent in the Y-direction by total internal reflexion of a plane wave coming with an incident angle θ_i . $n_{\text{sub}} = 10$, $n_{\text{amb}} = 1$.

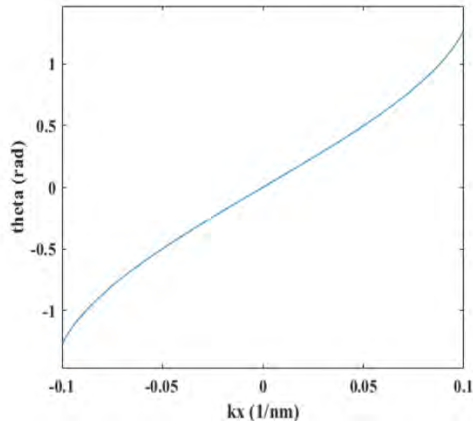


Fig.3: Corresponding between each k_x and incident angle θ_i for $n_{\text{sub}} = 10$.

The relationship between each k_x and incident angle θ_i follows relation (1) and is given Fig.3 [21].

$$\theta_i = \text{asin}(k_x / (k_0 \cdot n_{\text{sub}})) \quad (1)$$

The k_x spatial frequency has been discretized in 9 values: given in table 1 ($\times 2$ due to $\pm k_x$), corresponding to 9 incident plane waves with 9 different incident angles. For each wave the amplitude is given by the curve Fig.1b. The sum of these 9 waves is shown in Fig.4. Due to the discretization in the spatial domain (k_x) the two evanescent points sources appear to be periodized. The imaging process by a microsphere can now be studied.

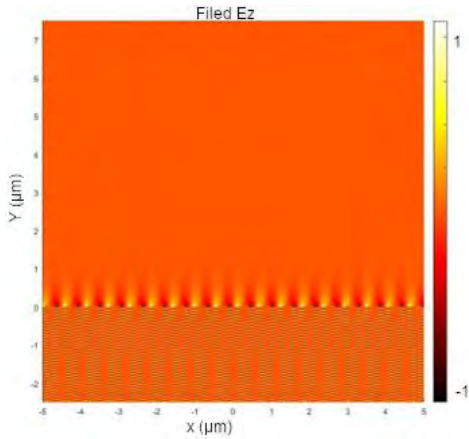


Fig.4: Electric field of an Array of two evanescent point sources 2 by 2 out of phase.

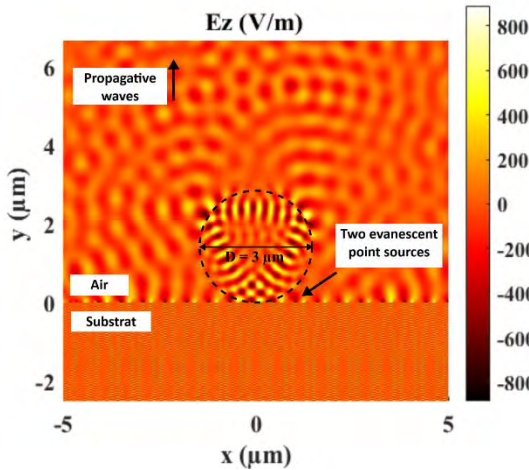


Fig.5: Electric field of evanescent point sources out of phase under a $3 \mu\text{m}$ glass microsphere.

III. IMAGING PROCESS SIMULATION

The interaction with a $3 \mu\text{m}$ glass microsphere (refractive index 1.5) is depicted in Fig.5. The coupling of the evanescent sources within the microsphere and their far field conversion is clearly visible.

The microsphere performs a virtual image. Therefore, the image cannot be directly observed. A time reversal propagation [22] in free space from the outgoing wave captured in the top of Fig.5 is required. This time reversal propagation is illustrated Fig.6. Two first maxima are visible at $y = -4 \mu\text{m}$. They correspond to the maxima of a stationary case inside the microsphere [21]. The virtual image is visible at $y = -12 \mu\text{m}$. The electric field norm $|Ez|$ in this plane has been extracted Fig.7. The two points are now separated by around $1 \mu\text{m}$. A magnification of around 5 can be deduced.

This simulation illustrates that the microsphere does not only convert near field evanescent waves in far field propagative waves. An imaging process takes place. This imaging process does not only concern the propagative waves but also the evanescent waves.

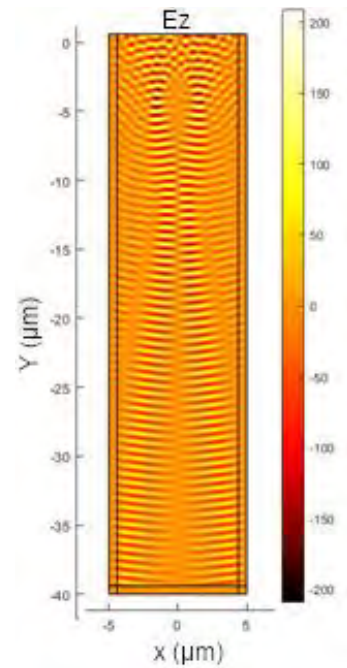


Fig.6: Electric field of the time reversal propagation in free space from the out going wave in the top of Fig.5.

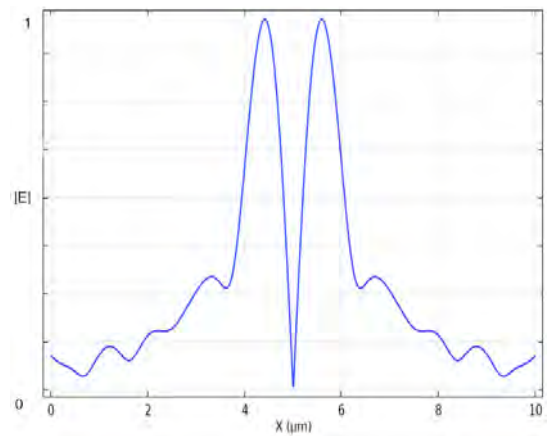


Fig.7: Electric field norm in the virtual image plane.

In a real experiment, there is no evanescent point source. The light interaction with the sample, and especially with the sub- $\lambda/2$ details, generates localized evanescent waves. Our simulations show that due to the sphere position, which is in the near field of the sample, the evanescent waves contribute to the imaging process and can therefore contribute to resolution increase.

However, all the evanescent waves do not contribute with the same proportion in the imaging process. Looking in detail, from the 9 considered value of k_x only the two first have been coupled to the microsphere. These couplings are represented Fig.8. This can be explained by two phenomena. On one hand, larger is k_x , smaller will be the decay length of the evanescent wave in the Y direction, making more difficult the electromagnetic coupling with the microsphere. On the second hand, the glass microsphere behaves as an open cavity with its own eigenmodes (the spherical harmonics). Therefore, as illustrated in [15] depending on k_x , and on the sphere diameter, some resonances can occur making the coupling more or less important. Fig. 8 shows that when the coupling occurs the evanescent waves are coupled to whispering gallery modes. It is very different from a classical lens. The microlens do not only contribute to the imaging process but modifies the spatial frequencies of the image. This may perhaps explain why experimentally on the same sample, the super-resolved image can be visible through one sphere but not through another one having a slightly different diameter.

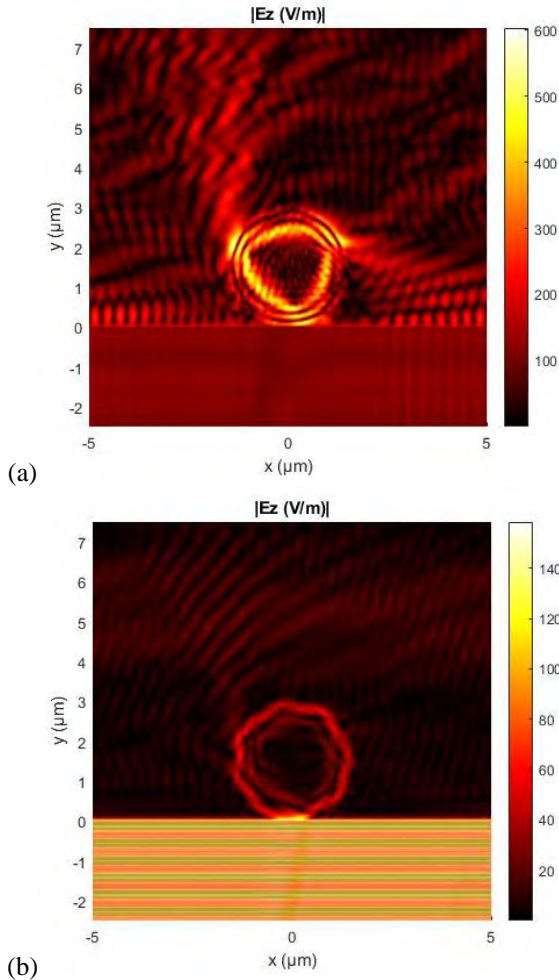


Fig.8: Electric field norm $|E|$ for the evanescent wave for (a) $k_x = 0,11 \text{ nm}^{-1}$ and (b) $k_x = 0,22 \text{ nm}^{-1}$, coupled with the glass microsphere.

IV. CONCLUSION

In this theoretical study we have shown how the concept of evanescent point sources can be used to understand the resolution of microsphere assisted microscopy. A microsphere can convert near field evanescent waves from a sample into far field propagative waves collected by a classical objective lens. More than a simple conversion, these waves contribute to a full field imaging process. The high spatial frequencies of these waves contribute to explain why in microsphere assisted microscopy a resolution beyond the diffraction limit can be reached. We have also shown that the microsphere behaves not as a classical lens but as a filter. The lower spatial frequencies are easier to collect due to their larger decay length. Moreover, the microsphere behaves as an open cavity with its own resonances.

TABLE I. SELECTED k_x VALUES.

$k_x \text{ [nm}^{-1}\text{]}$								
0,11	0,22	0,33	0,44	0,55	0,66	0,77	0,88	0,1

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