Numerical simulation of near-field focusing phenomena depending on the radius of curvature and the refractive index of microlens

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Abstract- **We report near-field focusing phenomena depending on the radius of curvature (ROC) and the refractive index of a microscale solid immersion lens (m-SIL) by finite-difference time-domain (FDTD) calculation. We show the clear effect of the ROC and the refractive index on the focal length and the focal-spot size, indicating the estimated resolution of the combined optical system.**

I. Introduction

As the resolution of standard lens-based optical microscope imaging system is limited by diffraction to ~ 250 nm, beating the Abbe's diffraction limit has been one of the primary interests of many areas of scientific research such as nanophotonics, bio-imaging optics and material science. Recently, diverse studies have been reported that near-field high resolution beyond the Abbe's diffraction limit can be achieved in dymanic real-time imaging only by a standard conventional optical microscope with a nanoscale solid immersion lens (n-SIL) or a dielectic microsphere [1]–[3].

However, it is quite challenging for most of nanopattern fabrication methods to implement n-SILs or microspheres configuration with desired geometries. Another practical limitation is, furthermore, alignment and positioning of those optical structures with the determined spot on the specimen surface [4].

In recent year, we have developed the novel methods for fabrication of shape-controllable and detatchable microscale solid immerson lens (m-SIL) and exact alignment on a specimen for overcoming these existing issues. Moreover, we have revealed that these optical structures can still resolve sub-diffraction-limited features although the radius of m-SIL remains relatively longer than the wavelength of illumination light, of which we consider more practical approach in terms of implementation.

In this paper, we investigate near-field focusing phenomena depending on the radius of curvature (ROC) and the refractive index of m-SILs by finite-difference time-domain (FDTD) method. We show the clear effects of the ROC and the refractive index of m-SILs on the focal length and the focal-spot size, indicating the estimated resolution of the combined optical system.

II. Simulation modeling details

Fig. 1 shows the schematic illustration of the imaging setup in which the m-SIL is placed on the specimen. Here, the structure of the specimen cannot be resolved by conventional optical microscopy due to the diffraction limit. We expect that the features of the specimen below the diffraction limit can be observed by carefully placing our m-SIL on the specimen.

Fig. 2 shows the electric field intensity distributions by FDTD simulation which demonstrate near-field focusing phenomena with different values of the ROC (radius of curvature) and the refractive index. From inspection of Fig. 2, it is clear that each parameters affect the focal length of the m-SIL, which refers to the spatial resolution of the whole imaging system. Fig. 2(a) and (b) graphically show the effect of the refractive index on focusing strength of m-SIL. The refractive indice of each m-SIL were set as (a) $n_{m\text{-}SIL}$=1.5 and (b) $n_{m\text{-}SIL}$ = 2.5, respectively. We note that shorter focal length can be obtained by choosing higher refractive index material. Fig. 2(c) and (d) show the curvature dependence of the m-SIL. We note that thicker lens exhibits shorter focal length, indicating higher resolution from the result of the simulation varying ROC of the lens.

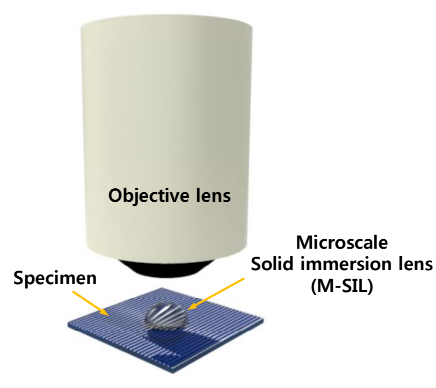

Fig. 1. Schematic illustration of the imaging setup in which the m-SIL is placed on the specimen (not to scale). Conventional microscopy with an objective lens imaging a specimen through a m-SIL

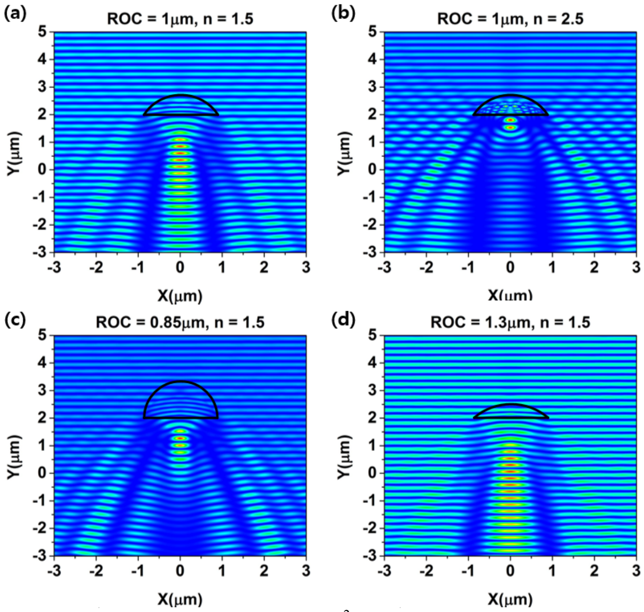

Fig. 2. FDTD simulation results of $|E_x|^2$ through m-SILs (TM polarized, λ = 0.472μm). (a) ROC : 1μm, $n_{M\text{-}SIL}$: 1.5 (b) ROC : 1μm, $n_{M\text{-}SIL}$: 2.5 (c) ROC : 0.85μm, $n_{M\text{-}SIL}$: 1.5 (d) ROC : 1.3μm, $n_{M\text{-}SIL}$: 1.5

III. RESULTS AND DISCUSSION

The full-width at half-maximum (FWHM) is a widely used evaluation of resolution. In order to estimate the resolution enhancement factor as a function of geometric and material parameter of the m-SIL, we quantitatively examine the focal spot profile along the x-axis varying each parameters, as depicted in Fig. 3. In order to provide insight for the tendency on parameters of m-SIL, we plotted the focal length and FWHM versus the ROC as illustrated in Fig. 4(a) and (b), respectively.

It should be emphasized that we can clearly see the dependance of the curvature and the refractive index of the m-SIL, which is the same qualititive behaviour to geometric optics' case from our results.

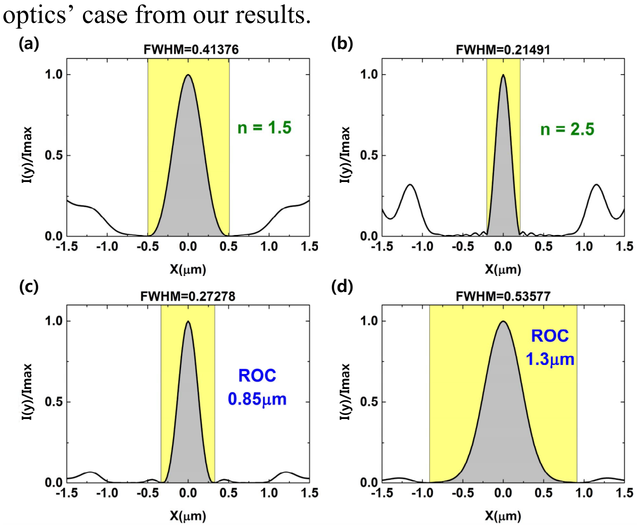

Fig. 3. Plots of the Full-width at half maximum (FWHM) with normalized intensity profiles at the focal spot as a function of ((a) and (b)) the refractive index of M-SILs and ((c) and (d)) ROC.

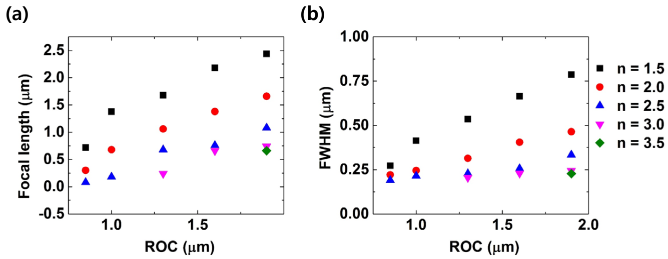

Fig. 4. Focal length and FWHMs of focal spot with different M-SILs: (a) ROC and (b) refractive indice.

IV. CONCLUSION

In summary, we have performed numerical simulations to investigate the focal length and the focal-spot size of micro-scale solid immersion lens with various curvatures and refractive indice. Additionally, near-field focusing effect depending on the wavelength of illuminated light also has to be considered. We hope that the theoretical understanding and the result of numerical simulation here would guide the experiments of the future work.

ACKNOWLEDGMENT

This work was partly supported by the Basic Science Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (2014R1A1A1005945), and by supported by MSIP as GFP / (CISS-2013M3A6A6073718).

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