Experimental mapping of near-field eigenmodes in sub-wavelength nanostructures

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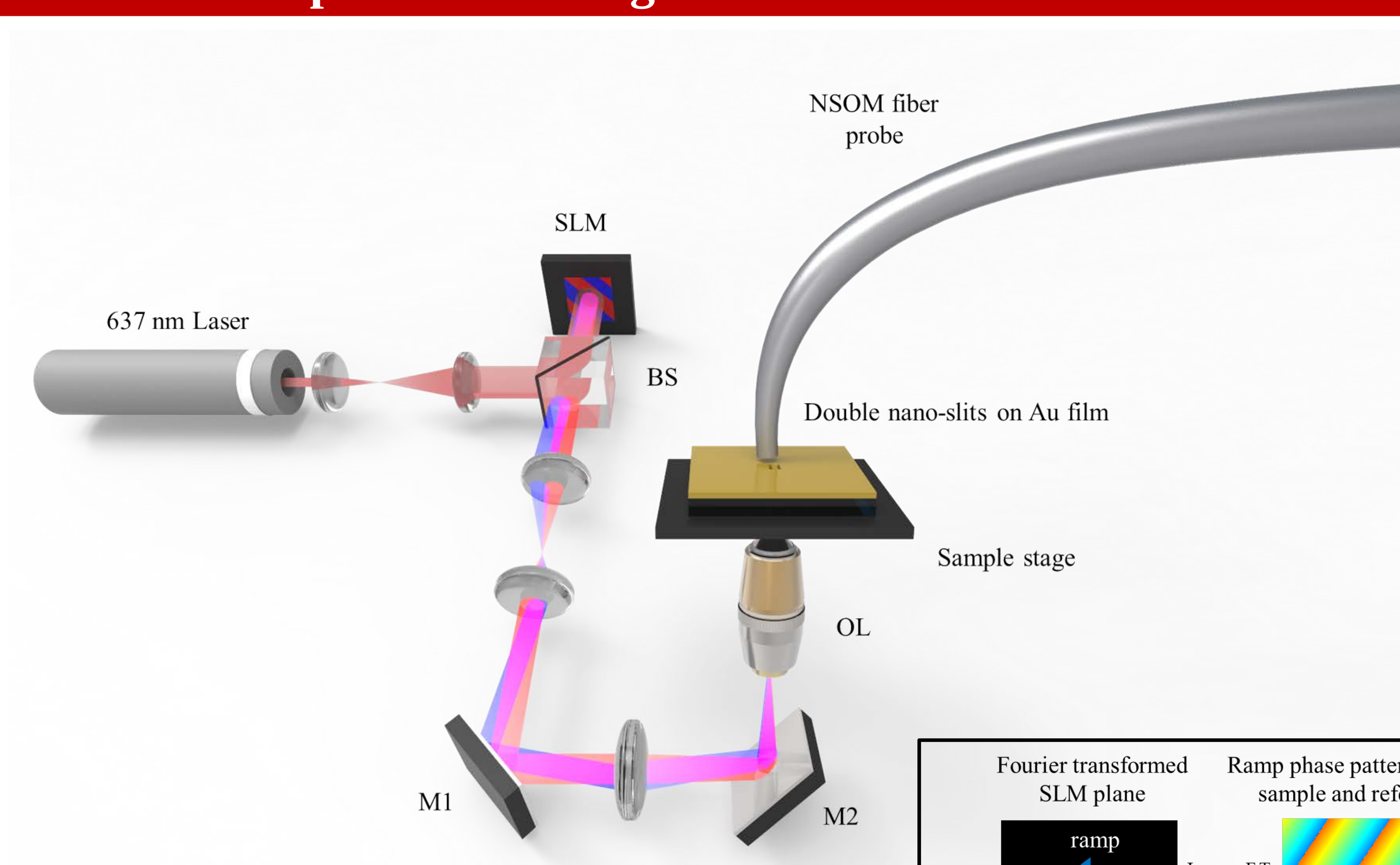
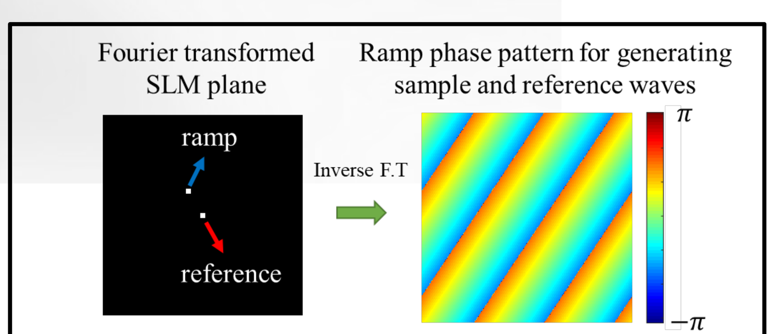
Abstract

Near-field scanning optical microscopy (NSOM) is a useful tool for studying sub-diffraction nanostructures. As the size of nanostructures becomes smaller, the ability to observe and manipulate the near-field is getting more crucial. In ordinary NSOM imaging, the illumination of light source has not been a major concern since the spatial resolution is mainly determined by the collection process by the sub-wavelength aperture.
We constructed a unique system that integrates far-field wavefront shaping by a spatial light modulator into an NSOM and developed methods to measure a far- to near-field transmission matrix (FNTM). Using the recorded matrix, we have demonstrated the manipulation of near-field waves and observation of the near-field eigenmodes generated by the nanostructures.
For the double-slot nanoantenna having the separation of 50 nm, which is about 13 times smaller than the wavelength of light source and 3 times smaller than the size of NSOM probe, we could obtain an anti-symmetric transverse mode which has a sharp phase singularity in the middle of the two slot antennas. This corresponds to the resolving of structures whose separation is smaller than the NSOM aperture. Moreover, by scanning the NSOM probe over the two-dimensional (2D) surface, we have demonstrated the mapping of 2D near-field eigenmodes for any arbitrary nanostructures. We believe that these studies exploiting the far- to near-field transmission matrix will open new venues for interrogating the complex nanophotonic structures.

Experimental setup for measuring the far- to near-field transmission matrix

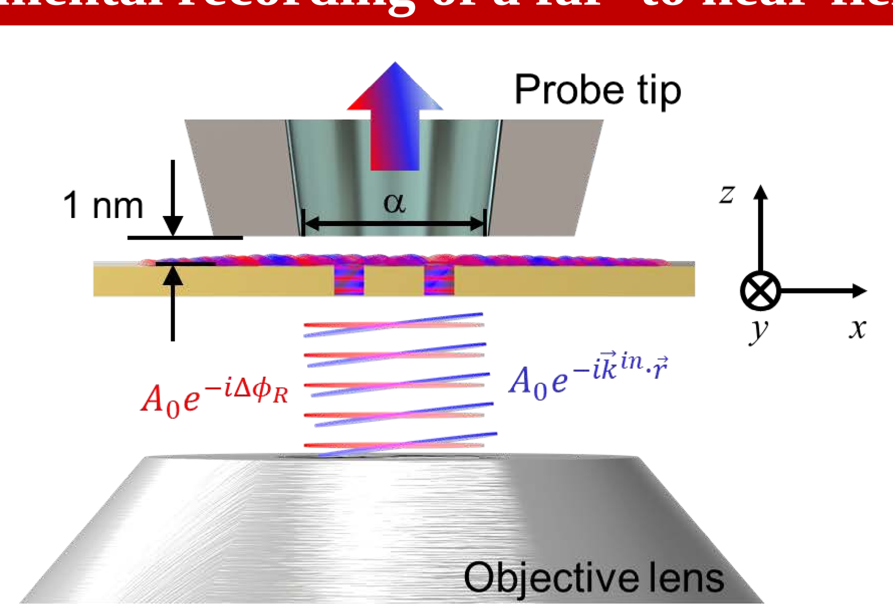


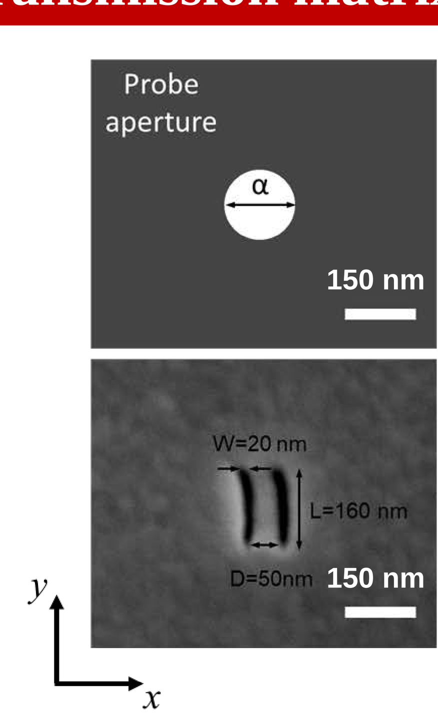
- We combined the wavefront shaping optics and near-field imaging system.
- Spatial light modulator generates both the reference and sample waves.

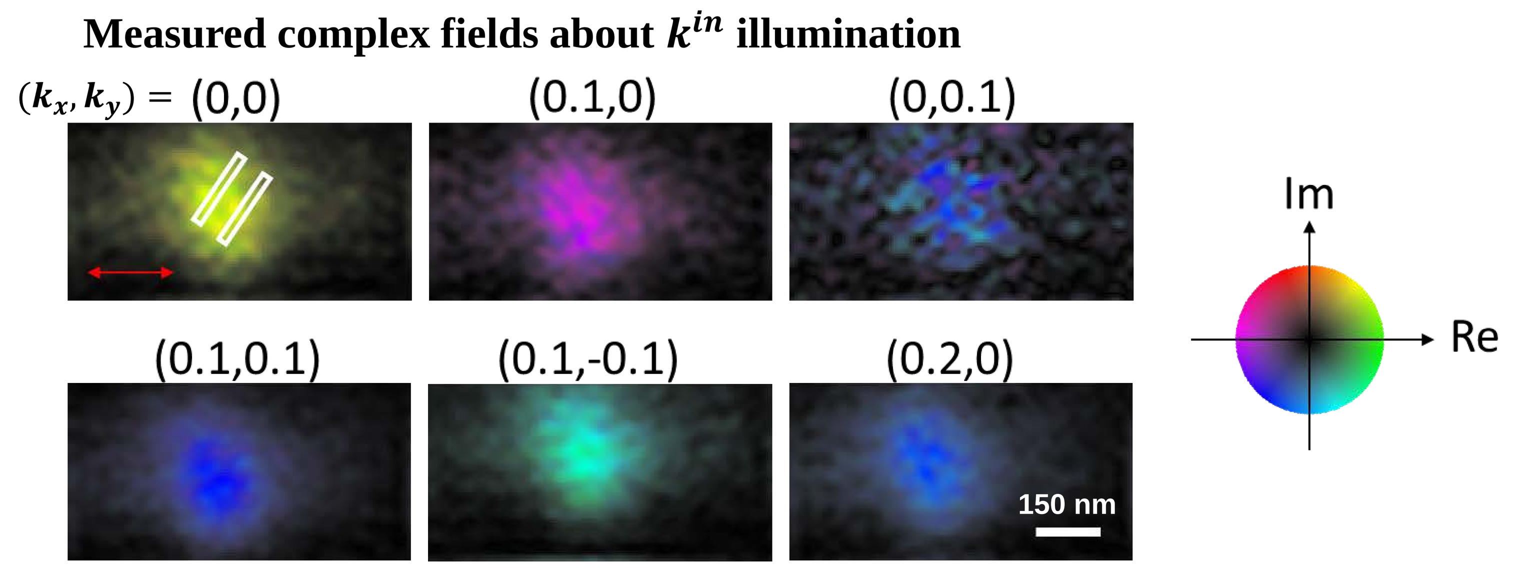


- We made 100 number of ramp basis to cover 0.6 NA of objective lens

Experimental recording of a far- to near-field transmission matrix

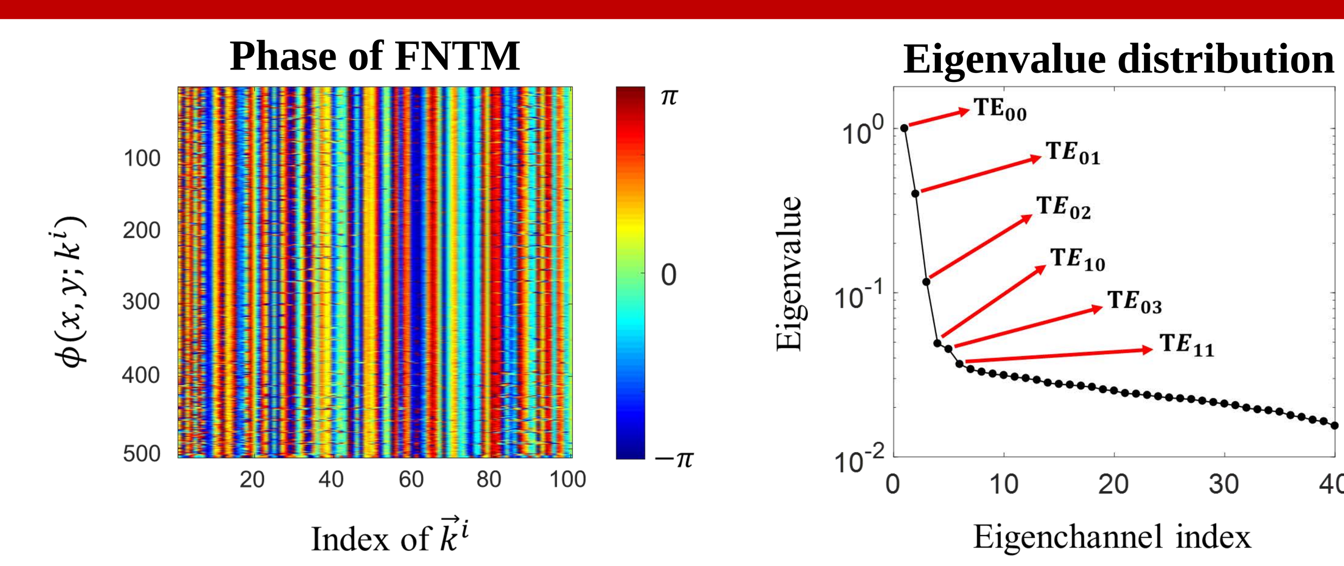


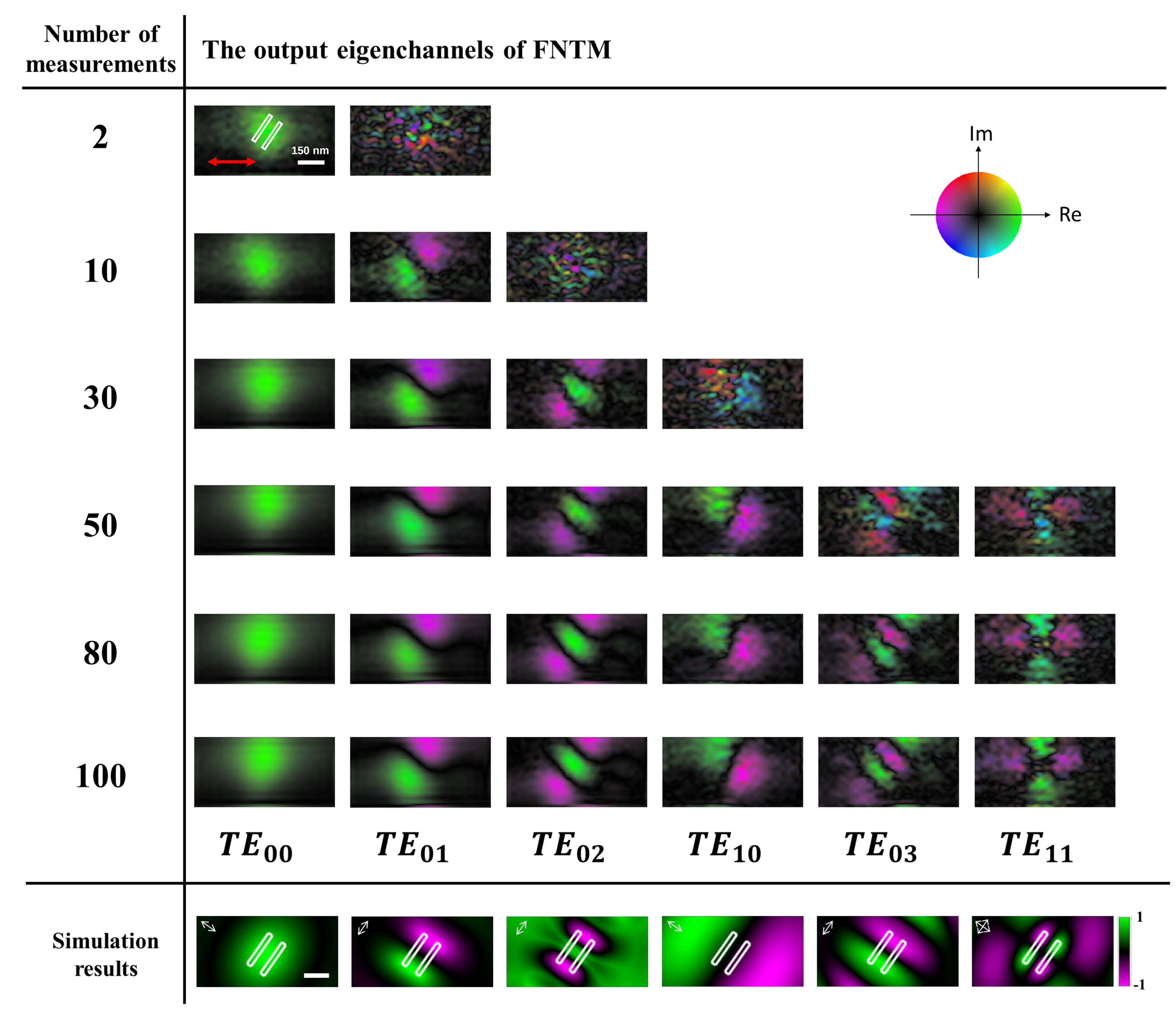




- 150 nm aperture corresponds to detection NA of $2k_0$~2.5 k_0.
- Measured complex fields of a single Gaussian map show the resolving power of the conventional NSOM imaging.

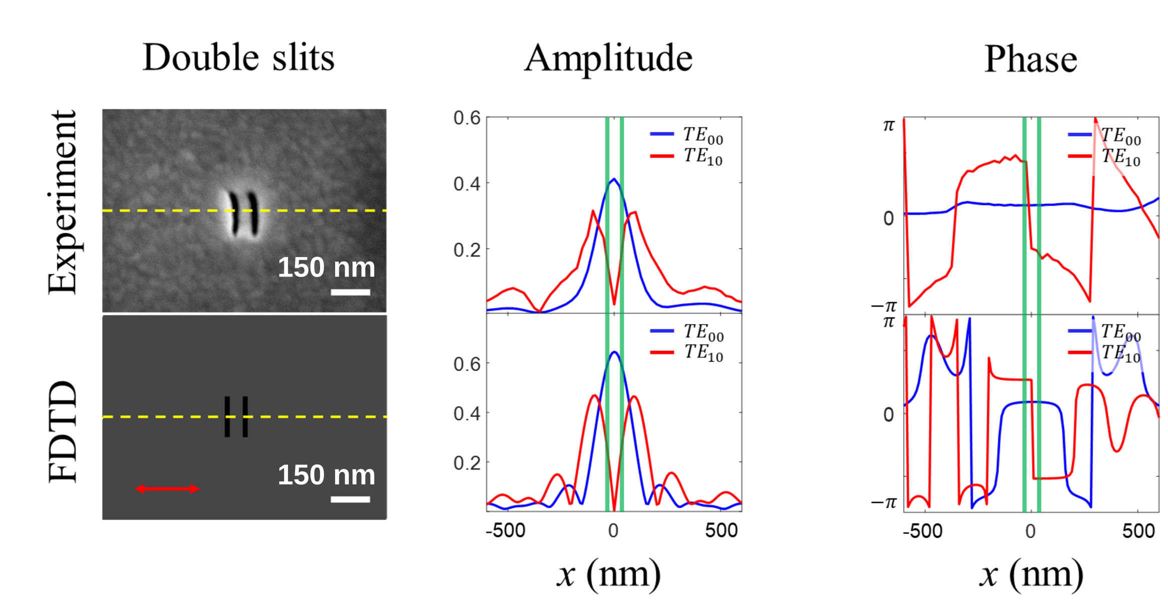
2-dimensional near-field eigenmodes mapping of arbitrarily rotated double slits

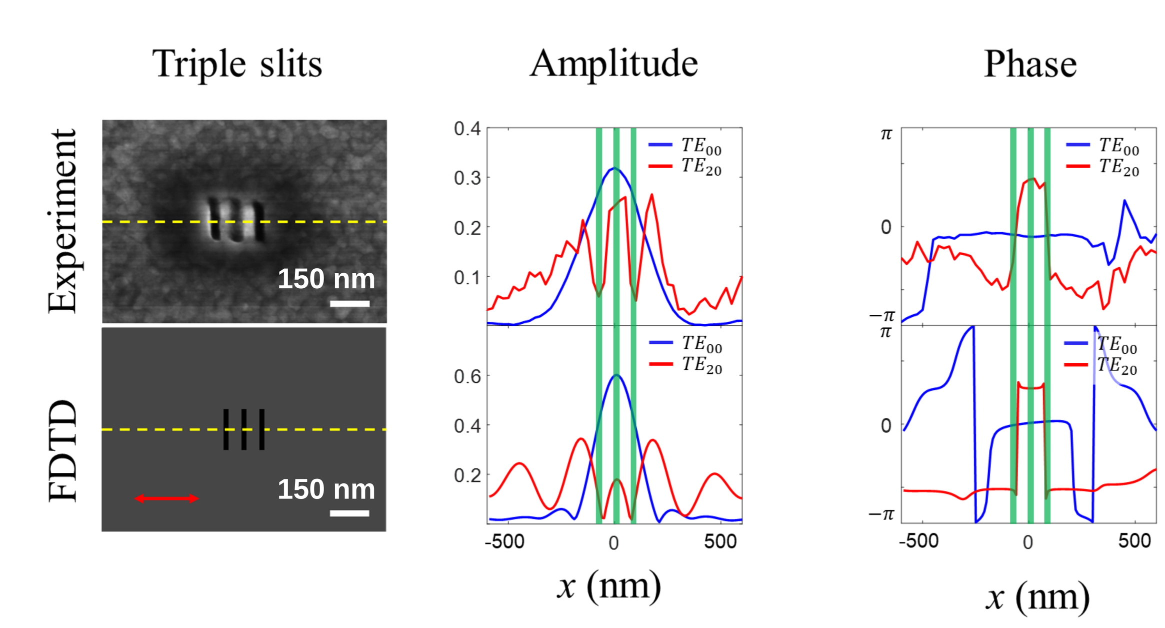




- By performing the singular value decomposition, various near-field eigenmodes could be identified.
- SNR of each mode depends on the number of measurements and the phase difference between nano-slits ($\Delta\phi_{max} \approx 0.1\pi$).
- We could estimate the amount of rotated angle as 34 degrees.

1-dimensional transverse modes mapping of double and triple slits





Conclusion

- We constructed a unique system for measuring the far- to near-field transmission matrix and demonstrated near-field eigenmode mapping of nano-slits structures whose gap is as small as 50 nm.
- We clearly resolved double and triple slits whose gap is much smaller than the NSOM aperture.
- By Performing the singular value decomposition of measured the FNTM, we could enhance the resolving power beyond the probe aperture limit.

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