Super-resolution 3D tomography of vector near-fields in dielectric resonators

FUDAN UNIVERSITY

Bingbing Zhu[1,2,†], Qingnan Cai[1,2,†], Yaxin Liu[1,2,†], Sheng Zhang[1,2,†], Weifeng Liu[1,2], Qiong He[1,2], Lei Zhou[1,2,*], Zhensheng Tao[1,2,*]

[1]State Key Laboratory of Surface Physics, Key Laboratory of Micro and Nano Photonic Structures (MOE), and Department of Physics, Fudan University, Shanghai 200433, China.

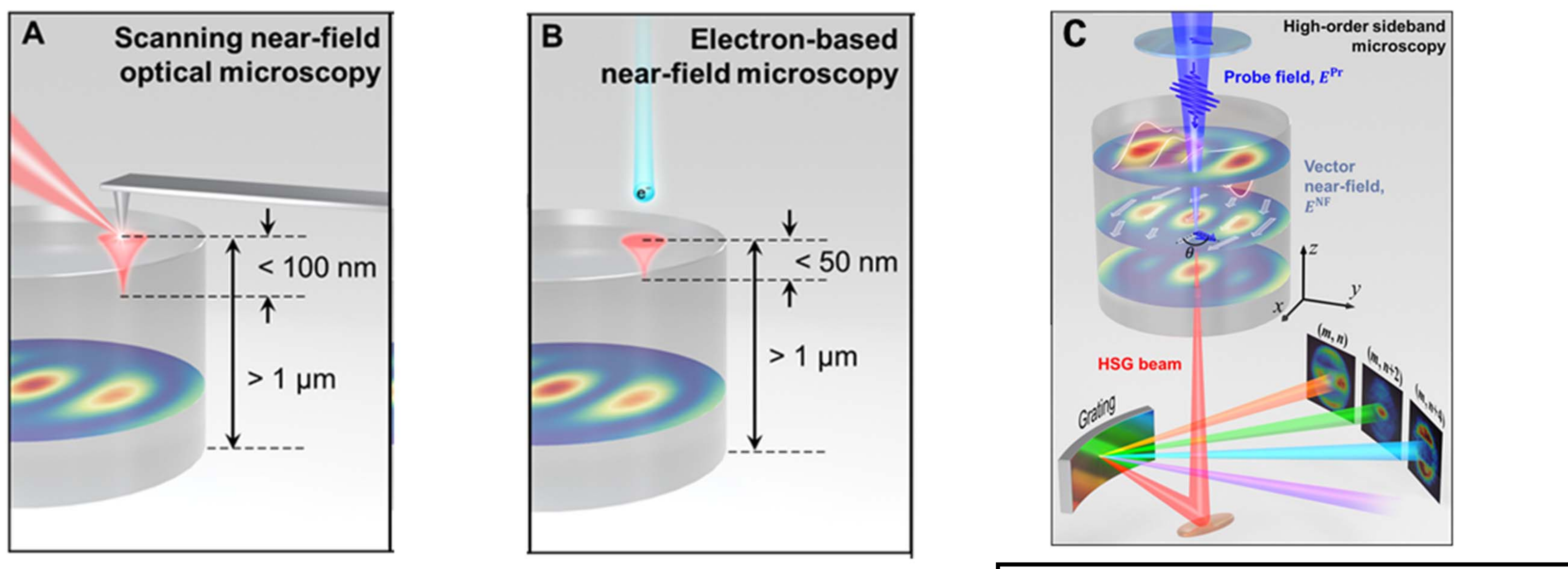
[2]Shanghai Key Laboratory of Metasurfaces for Light Manipulation, Fudan University, Shanghai 200433, China.

*Corresponding authors: Zhensheng Tao (ZhenshengTao@fudan.edu.cn), and Lei Zhou;

Ⅰ Introduction

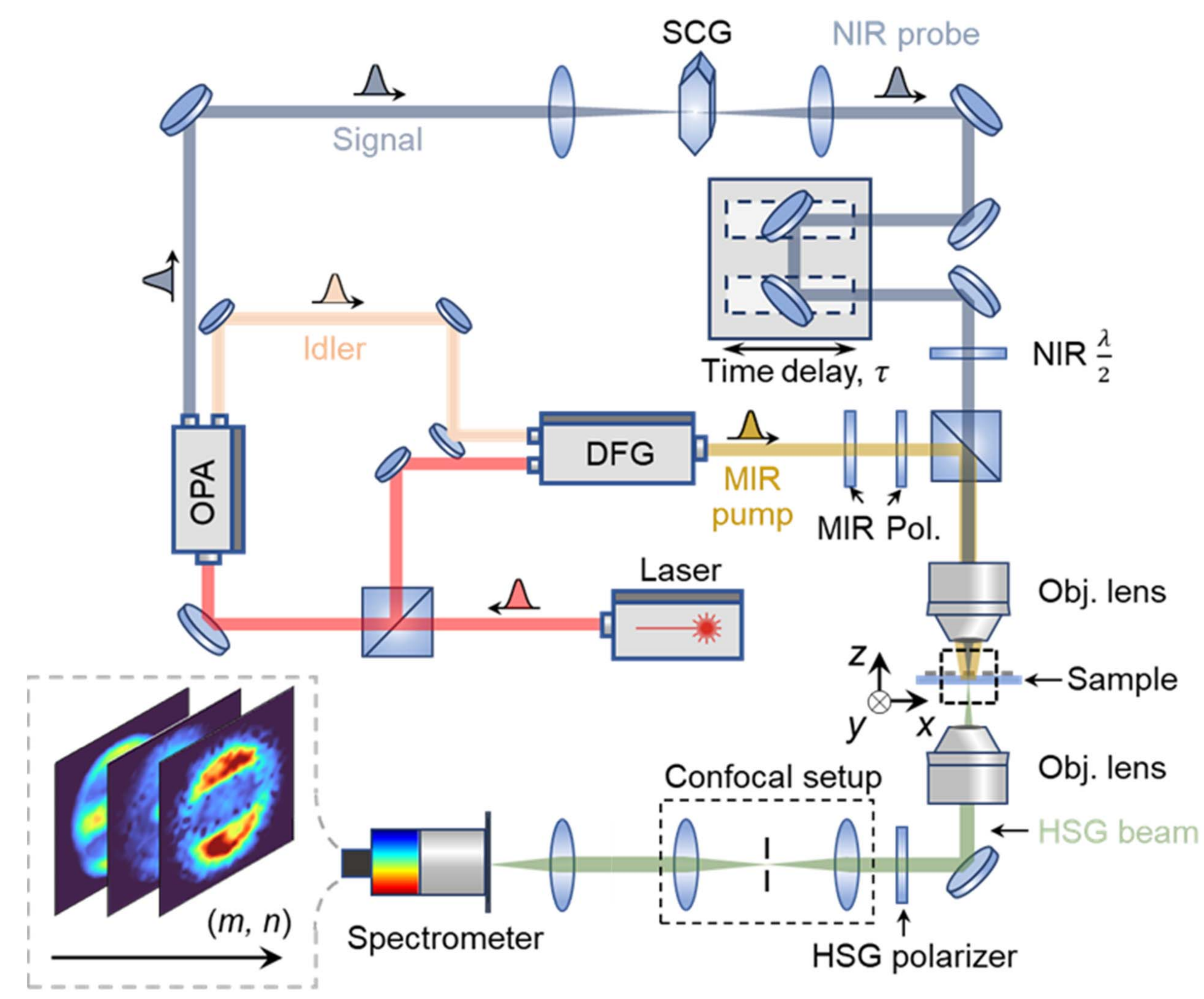
How to image near-fields inside a dielectric resonator, E^{NF}?

- tip-based (**A**) or electron-based (**B**):
  high resolution, but only surface sensitive
- Nonlinear optics:
- deep inside the dielectric !



Probe field, E^{Probe} :
focused spot, size ≃ 1µm

Ⅱ Experiment setup



- The near-field is excited by mid-infrared pulse (**duration ~200 fs, λ_{NF}=14 um** and repetition rate 5 kHz), generated by the difference frequency process (DFG) in 500um GaSe crystal.
- The probe pulse (**~150fs, ~1µJ, λ_{Pr}= 0.97µm**) is generated from YAG supercontinuum, the **spectral range is tunable** by spectral bandpass filters.
- By focusing the pulses together on the sample, sideband harmonics are generated.
- Confocal geometry is applied, and **images are taken by scanning the sample transversely.**

Ⅲ Main Results

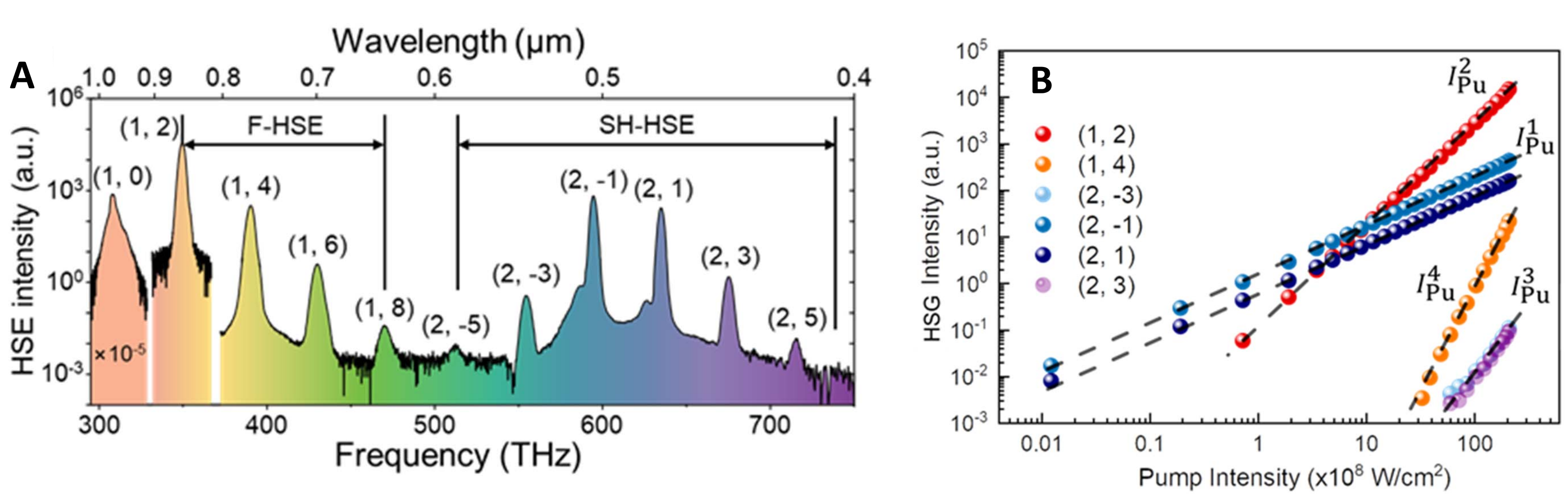
1. High-order sideband microscopy (HSM)

Nonlinear wave mixing: $P \propto \epsilon_0 \chi^{(m,n)} \left(E^{Probe}\right)^m \cdot \left(E^{NF}\right)^n$

m-probe ✚ n-near-field photons

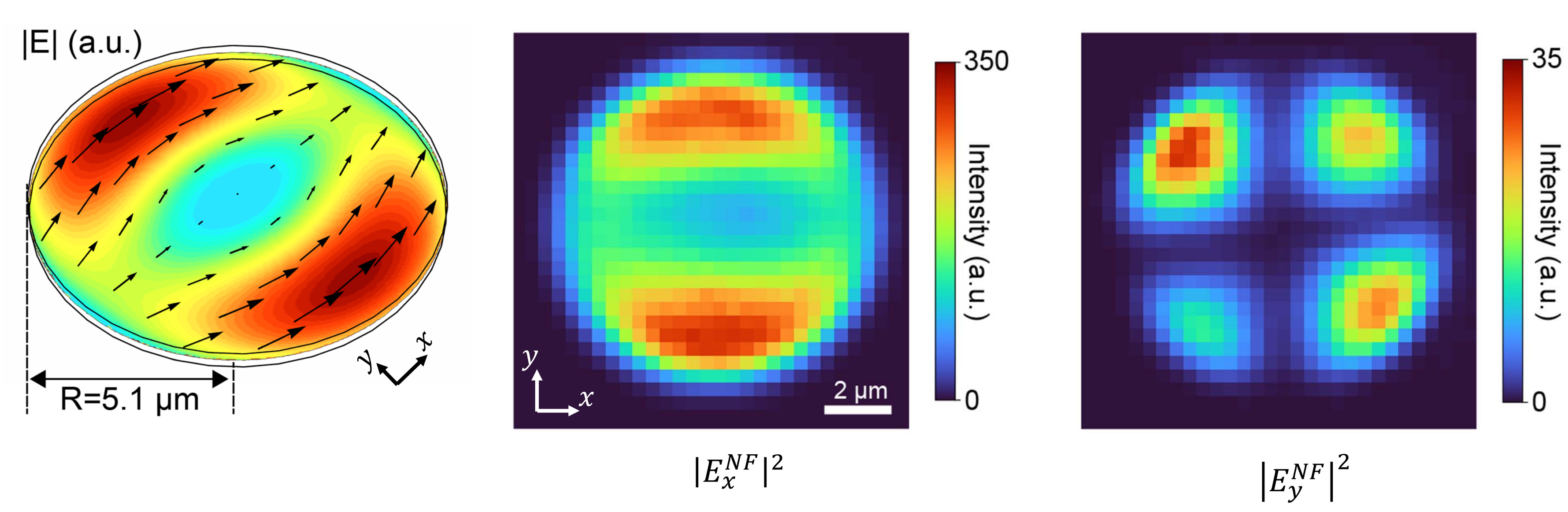
Radiated frequency: $f_{(m,n)} = mf_{Probe} + nf_{NF}$

Imaging "E^{NF}": **High-order sideband brings E^{NF} to the far field radiation!**



A: typical sideband spectrum measured on 1.5µm-thick silicon film, probed at $\lambda_{Pu} = 0.97$µm, near-field excited at $\lambda_{NF} = 14$µm.
B: energy-dependence of sidebands on the excitation (NF) intensity.

2. Polarization resolved near-field imaging



- **Left:** The near-field of a silicon resonator at **λ_{NF}=14 um** excitation (radius=5.1µm, thickness=0.5µm)
- **Mid & right:** The x and y polarized components of near-field measured by HSM. **Resolution=0.9µm.**

How? Symmetry of tensor $\chi^{(m,n)}$ for order (m,n)=(2,1)➔
Sense different near-field polarizations by varying probe's polarization direction

3. Tomography imaging

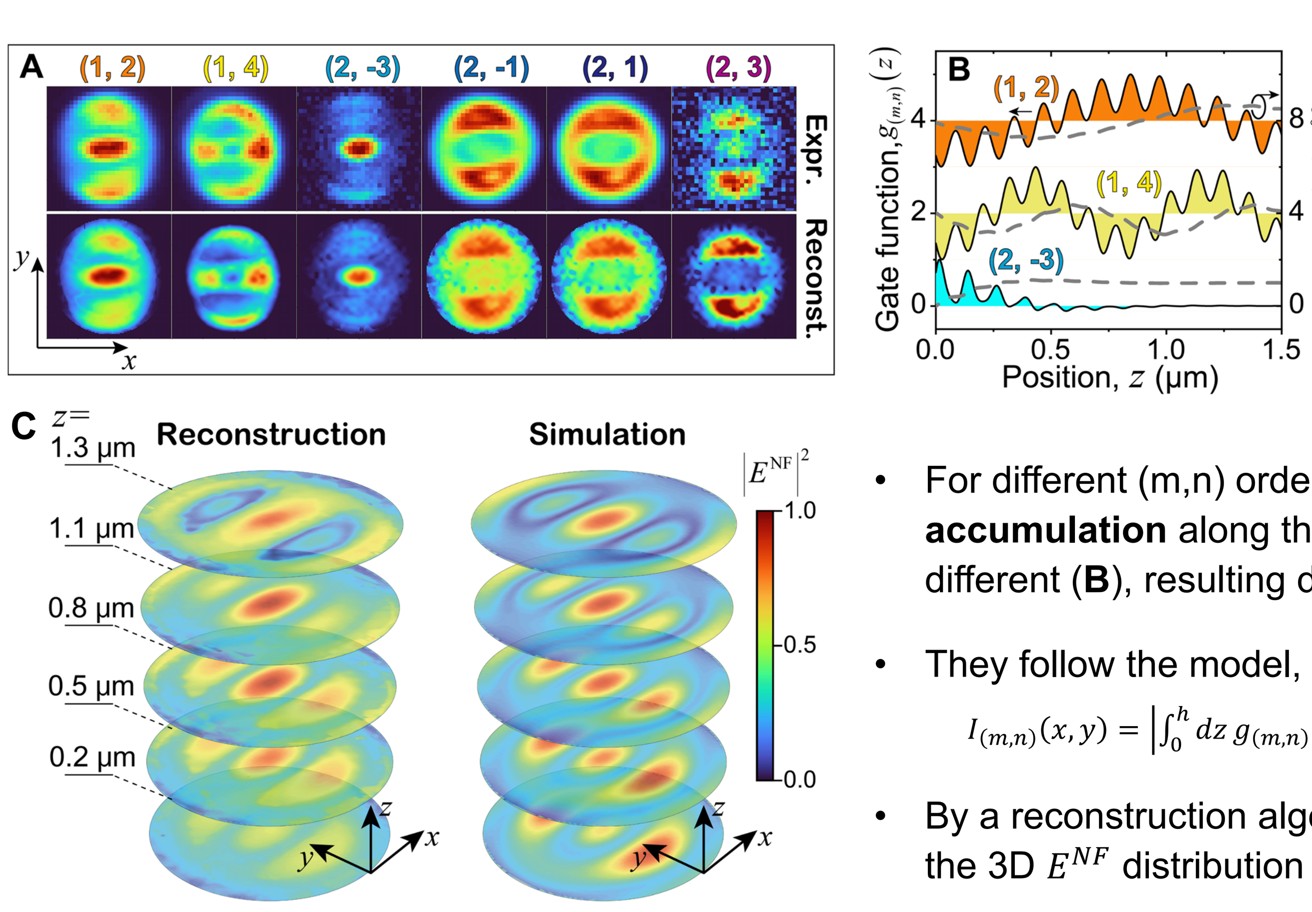
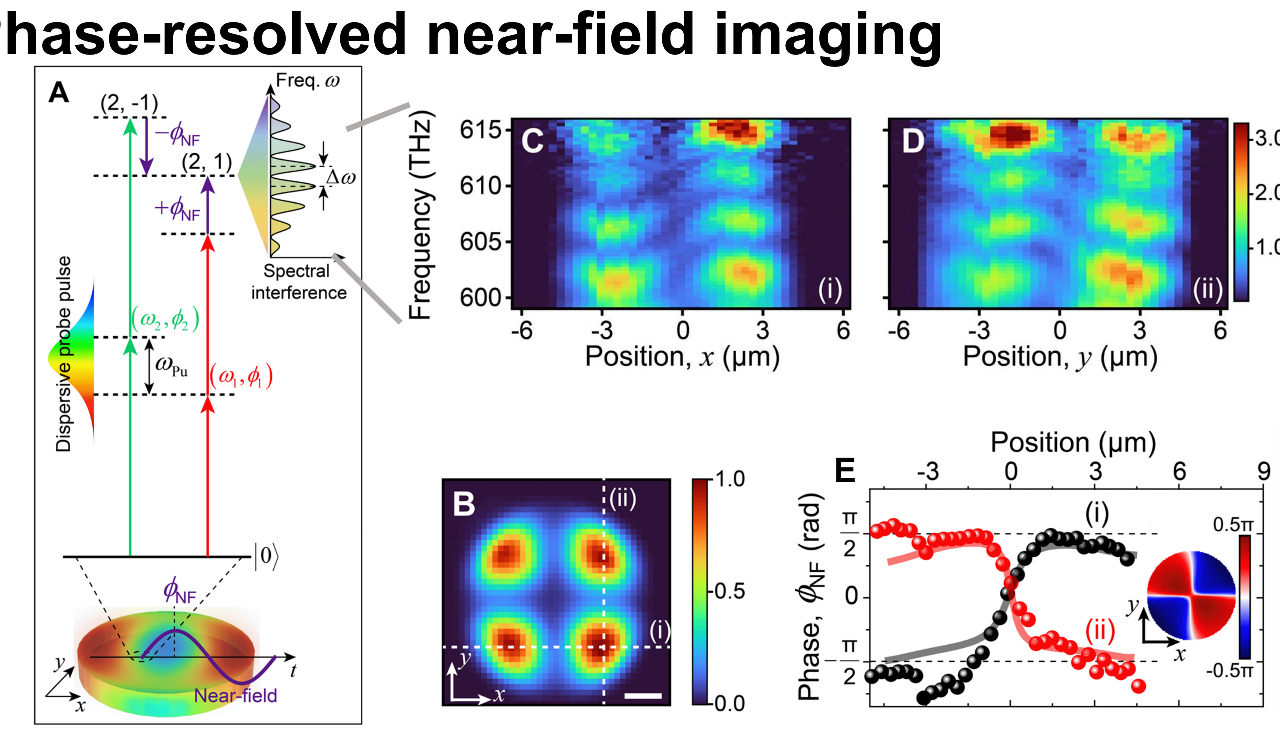


Figure: Tomography for a silicon resonator, x-polarized field. (thickness=1.5µm, radius=5.6µm)

- For different (m,n) orders, the way of signal **accumulation** along the thickness direction are different (**B**), resulting different images (**A**).
- They follow the model,
  $$I_{(m,n)}(x,y) = \left|\int_0^h dz\, g_{(m,n)}(z)\left[E^{NF}(x,y,z)\right]^n\right|^2$$
- By a reconstruction algorithm, we could recover the 3D E^{NF} distribution (**C**, left).
- By comparing with finite-element simulations (**C**, right), the accuracy of our method is checked. **Uncertainty along z: 0.13µm.**

4. Phase-resolved near-field imaging



Resolving the near-field instantaneous phase by inter-sideband interference:

A. The probe pulse is broadband and dispersive, resulting spectral overlap between order (2, -1) and (2, 1). Spectral modulation patterns appear, which dependent on the near-field phase under detection.

B. We experimental scanned probe spot along trajectories (i) and (ii) for y-pol of near-field,

C, D. The spectral modulations for (i) and (ii) "shifted" , which correspond to the variance of instantaneous near-field phase.

E. The measured instantaneous phases (dots) along (i) and (ii), compared with simulations (solid lines). Inset: simulated 2D phase distributions for the resonator.

Ⅵ Conclusion

- We demonstrate 3D tomographic, super-resolution and vector near-field imaging deep inside micrometer-thick dielectric optical resonators.
- The HSM technique demonstrated here could be applied to many other laser-induced wave phenomena beyond resonant near-fields. These include hyperbolic phonon-polaritons, topological photonic edge states, among others.