Mueller-matrix scattered-field microscopy for the measurement of finite deep sub-wavelength nanostructures

Xiuguo Chen*, Cai Wang, Tianjuan Yang, Jing Hu, Jiahao Zhang, and Shiyuan Liu

Email: *xiuguochen@hust.edu.cn

Nom Group: *http://nom.mse.hust.edu.cn*

State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China.

Introduction

- We propose Mueller-matrix scattered-field microscopy (MSM) that is capable of quantitatively determining geometrical parameters of finite deep sub-wavelength nanostructures.
- The MSM instrument employs a high-NA objective lens to collect a broad range of spatial frequencies of the scattered field in terms of Mueller-matrix images, and a rigorous forward scattering model is established for MSM to reconstruct nanostructures.

Experimental setup

The MSM instrument employs a high-NA (NA = 0.95) objective lens to collect a broad range of spatial frequencies of the scattered filed in terms of Mueller-matrix images.

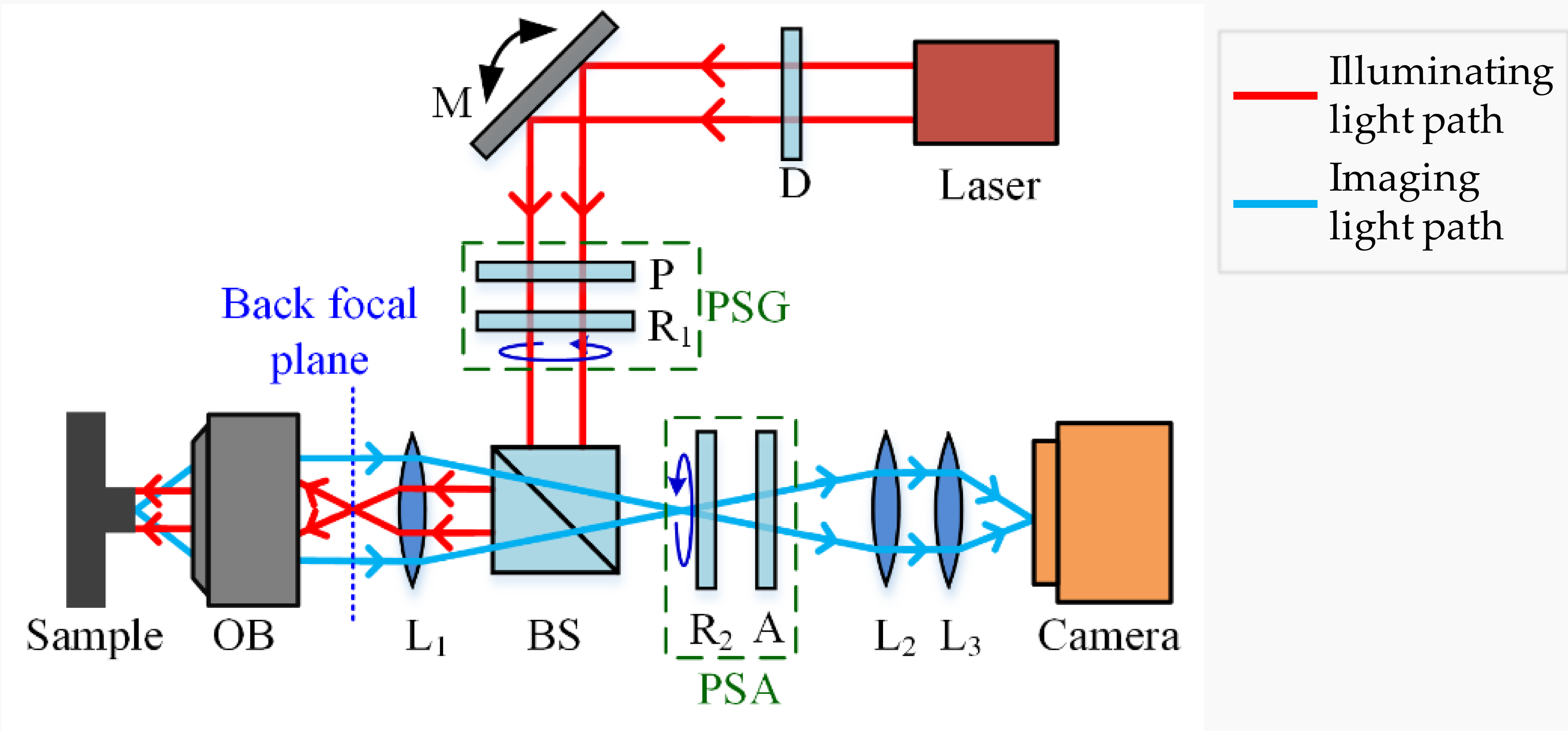
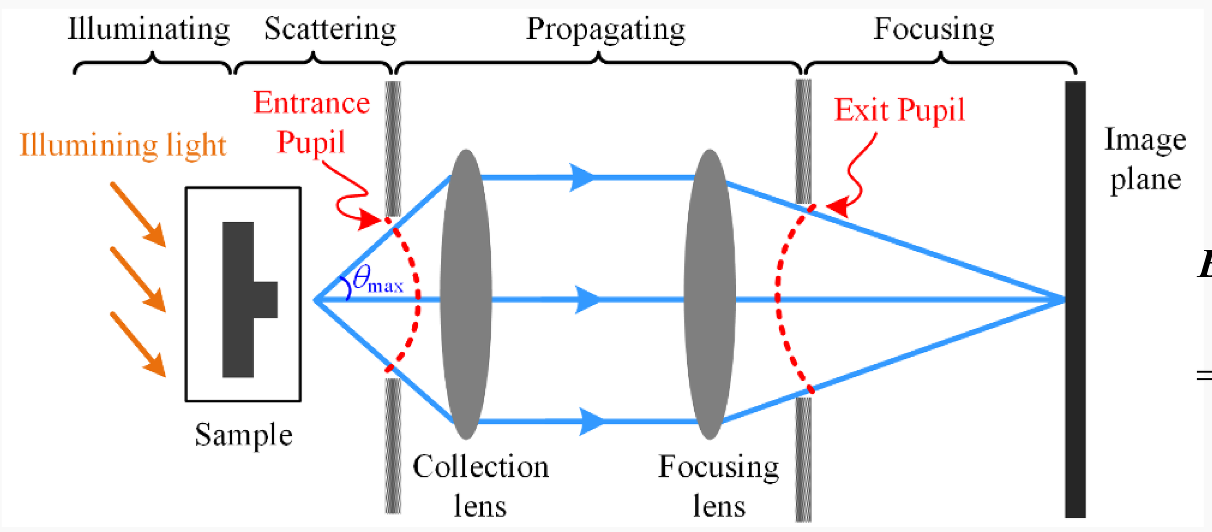


Figure 1. Scheme of the MSM. D: diffuser; M: mirror; P: polarizer; R_1, R_2: phase retarder; BS: beam splitter; OB: objective lens; A: analyzer; L_1~L_3: lenses; PSG: polarization state generator; PSA: polarization state analyzer. The two phase retarders R_1 and R_2 rotate synchronously at a speed ratio of 5:3 to achieve full Mueller-matrix measurement.

Forward scattering model for MSM



Scattered field on the image plane:

$$\boldsymbol{E}^{\text{image}}(x,y,z) = -\frac{\mathrm{i}}{\lambda}\iint_{\Omega}\frac{\left(E_s^{\text{exit}}\cdot\hat{\boldsymbol{s}}+E_p^{\text{exit}}\cdot\hat{\boldsymbol{p}}\right)}{r_z}e^{ik(r_x x+r_y y+r_z z)}\,\mathrm{d}r_x\mathrm{d}r_y$$

Figure 2. The forward scattering model for MSM, which takes into account the vectorial nature of the scattered field when passing through the imaging system and the effect of defocus in the measurement process.

Experimental results

To demonstrate the capability of MSM for measuring finite deep subwavelength nanostructures, a series of isolated Si lines with nominal widths from 20 nm to 120 nm in a 20 nm interval and a nominal height of 50 nm has been prepared and measured by MSM.

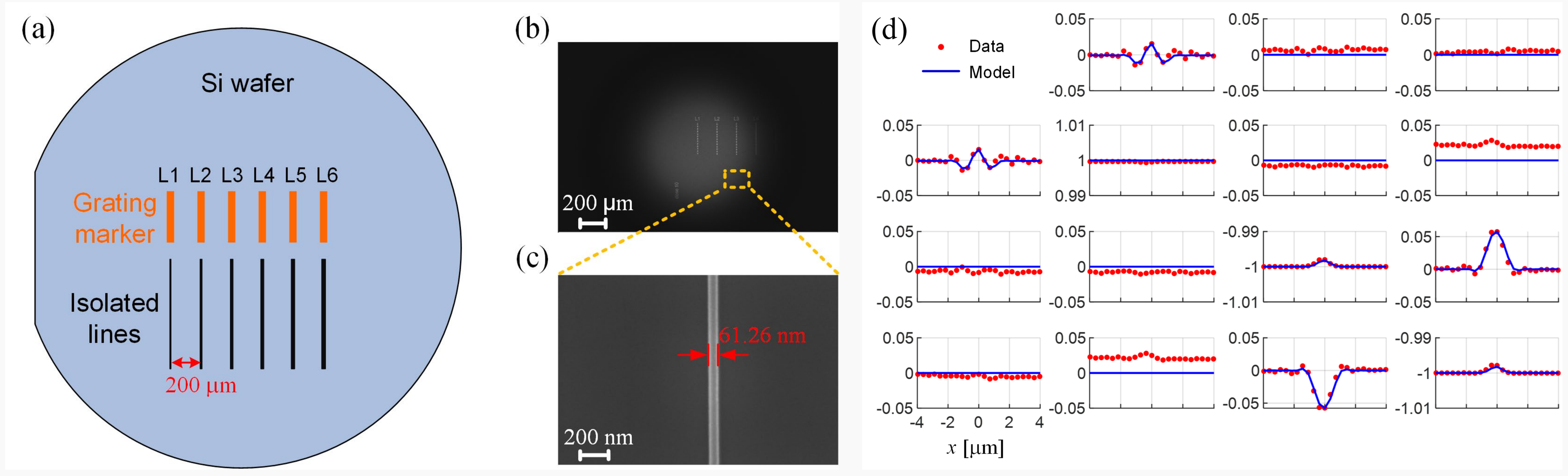


Figure 3. (a) The layout of the isolated Si lines on the Si wafer; (b) The SEM micrograph of the investigated isolated Si lines; (c) The SEM micrograph of the line with a nominal width of 60 nm; (d) The best-fit calculated and measured Mueller matrices of the isolated Si line with a nominal width of 100 nm at the normal incidence.

Table 1. Comparison of the measured width of isolated Si lines from MSM and SEM measurements. The uncertainties appended to MSM- and SEM-measured values all have a 95% confidence level.

SEM (nm)	120.7 ± 2.36	100.9 ± 2.70	79.3 ± 2.90	61.3 ± 2.56	41.4 ± 1.76	19.8 ± 1.78
MSM (nm)	113.6 ± 14.4	106.9 ± 10.3	86.1 ± 4.29	67.4 ± 2.66	47.4 ± 2.77	12.5 ± 3.90
Relative Error	5.87%	5.94%	8.63%	9.98%	14.34%	37.06%

Conclusions

- We have proposed a new approach called MSM that relies on a computational reconstruction strategy to quantitatively determine geometrical parameters of finite deep sub-wavelength nanostructures.
- The experimental results performed on a series of isolated Si lines have demonstrated that MSM can resolve a feature size of $\lambda/16$ with a sub-7 nm accuracy.

References

1. Y. Tan, C. Chen, X. Chen, et al., "Development of a tomographic Mueller-matrix scatterometer for nanostructure metrology," *Rev. Sci. Instrum.* **89**, 073702 (2018).
2. C. Wang, X. Chen, C. Chen, et al., "Reconstruction of finite deep sub-wavelength nanostructures by Mueller-matrix scattered-field microscopy," *Opt. Express* **29**, 32158-32168 (2021).