Designing of multilayers for evanescent wave-based interference lithography

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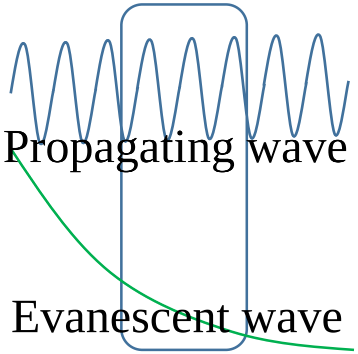
Nano patterning

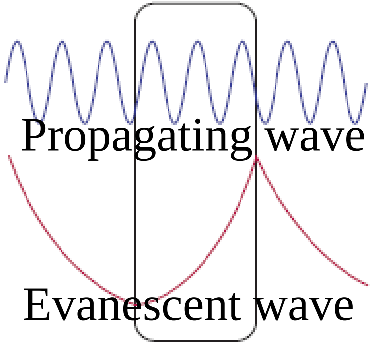
❑ Conventional photolithography

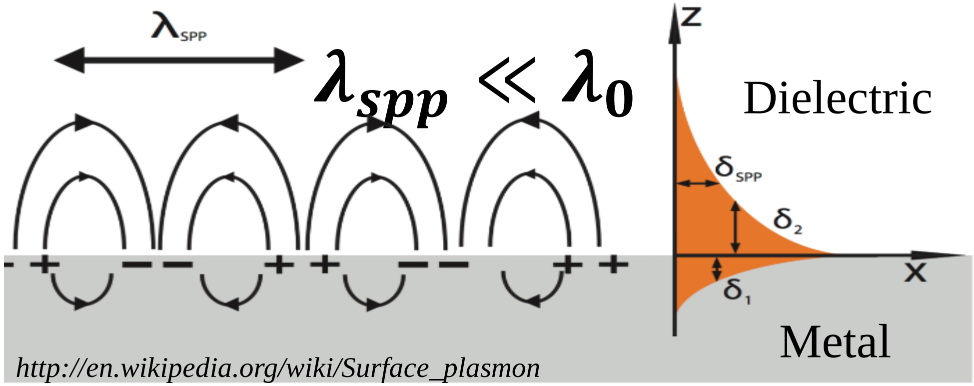


$$\text{Resolution:}\ \ \Delta = k\,\frac{\lambda}{NA} \qquad \left.\begin{matrix} \lambda\downarrow \\ NA\uparrow \end{matrix}\right\}\ \Delta\downarrow$$

❑ Plasmonic lithography

Super resolution





$$\lambda_{spp} \ll \lambda_0$$

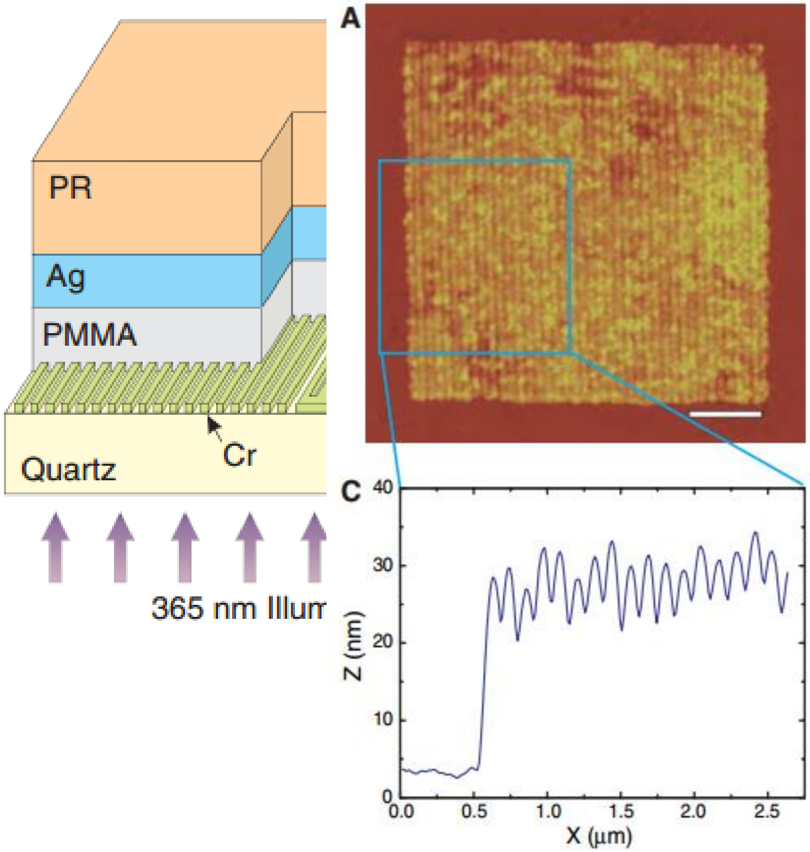
http://en.wikipedia.org/wiki/Surface_plasmon

Surface Plasmon Polariton (SPP)

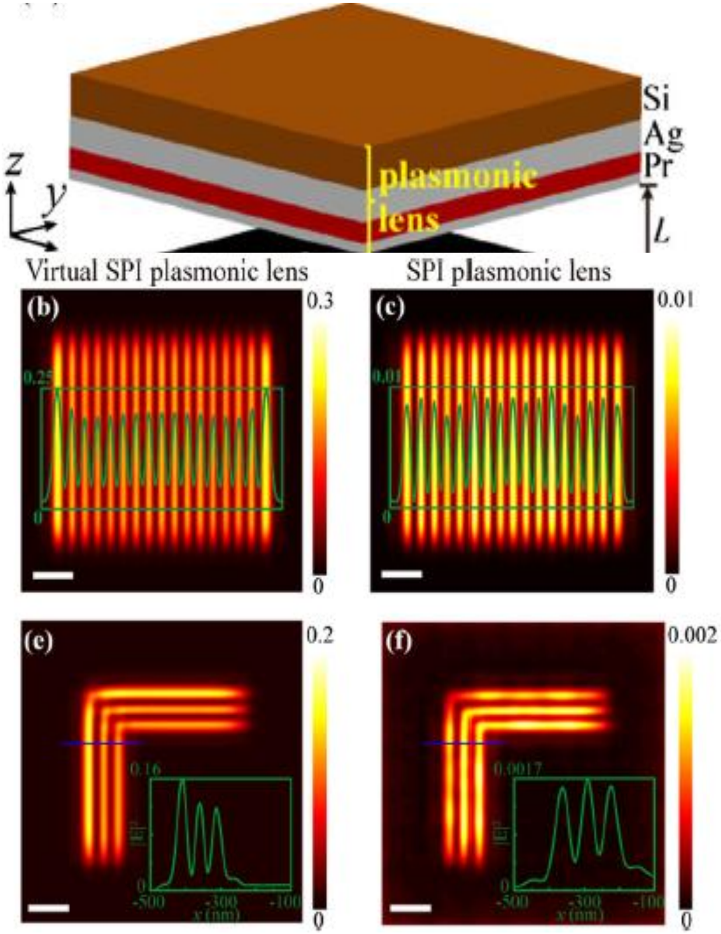
$$\lambda_{spp} = \lambda_0\sqrt{\frac{\epsilon_m + \epsilon_d}{\epsilon_m \epsilon_d}} \ll \lambda_0$$

Current Problems

- Shallow depth, Low contrast, High loss



N. Fang, et al., Science 2005, 308: 534

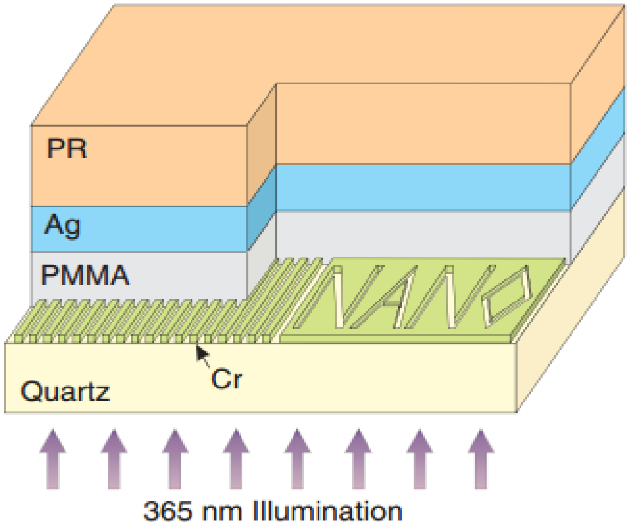


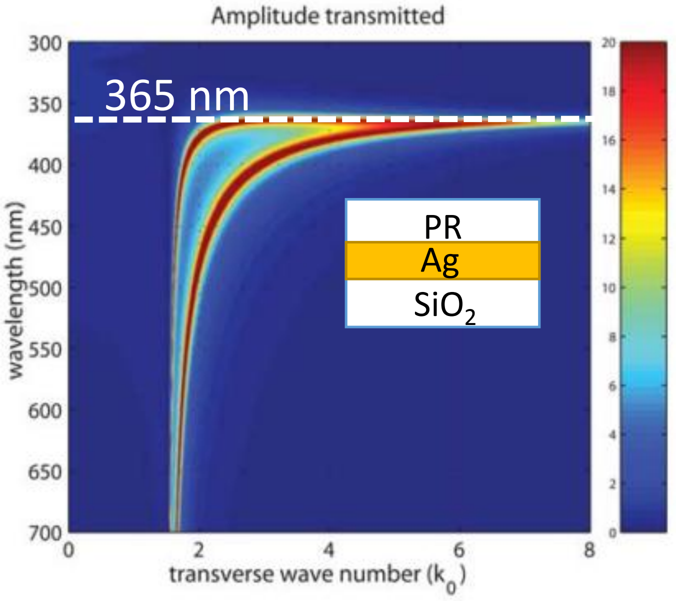
W. Zhang, et al., Plasmonics 2015, 10: 51

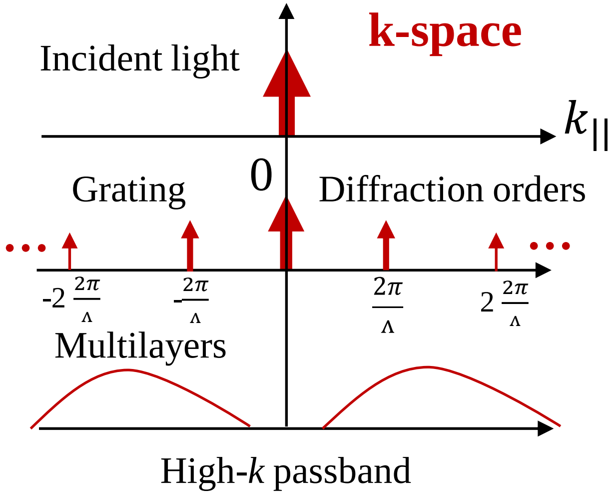
❑ Shallow depth ← Surface wave

❑ Low contrast ← Multiple *k*

❑ High loss ← Metal





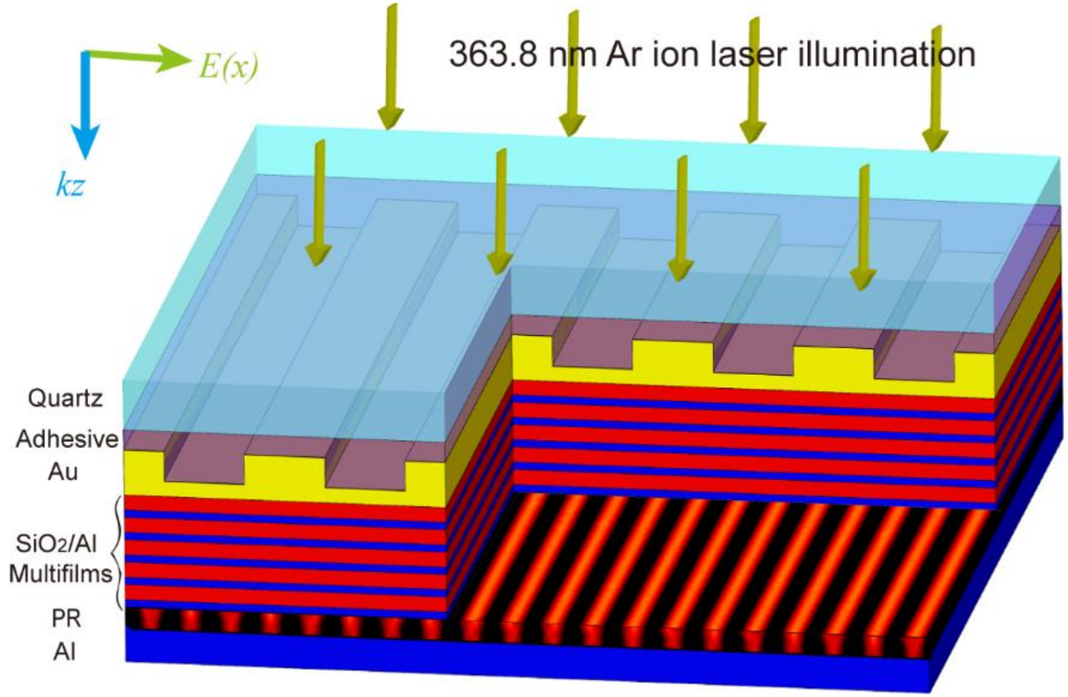


S. Durant, et al., J. Opt. Soc. Am. B 2006, 23: 2383

X. Chen, et al., ACS Nano 2016, 10(4): 4039

Target

- ❑ High contrast, High aspect ratio, Low loss

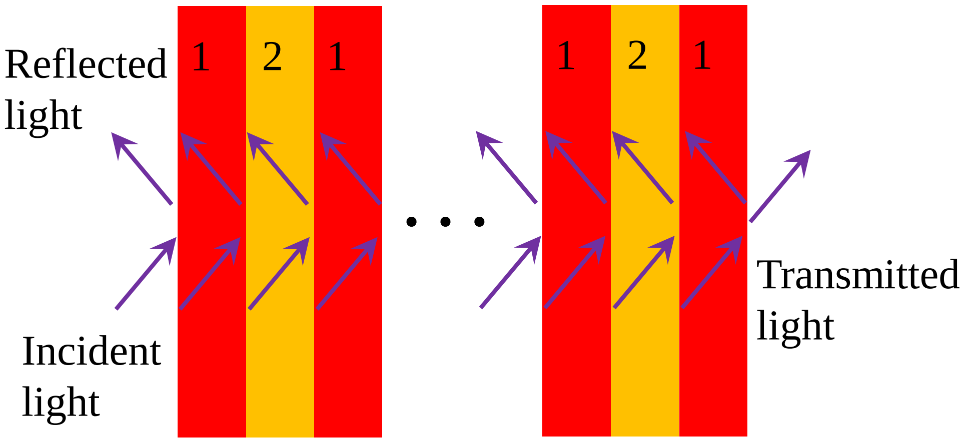


- ➢ Evanescent waves-based interference lithography
- ➢ The feature size is much smaller than the working wavelength

Method

❑ Employing multilayers

Hyperbolic metamaterials, epsilon-near-zero metamaterials, photonic crystal

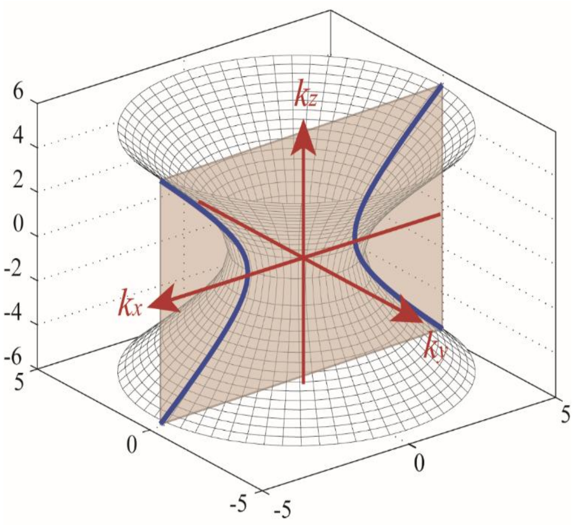


Reflected light

1 2 1 . . . 1 2 1

Incident light

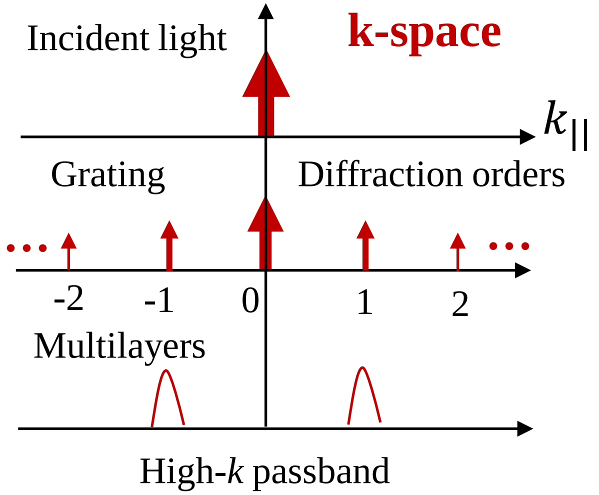
Transmitted light



- Multilayers enable multi-freedom adjustment
- low loss materials would be used in evanescent wave-based lithography

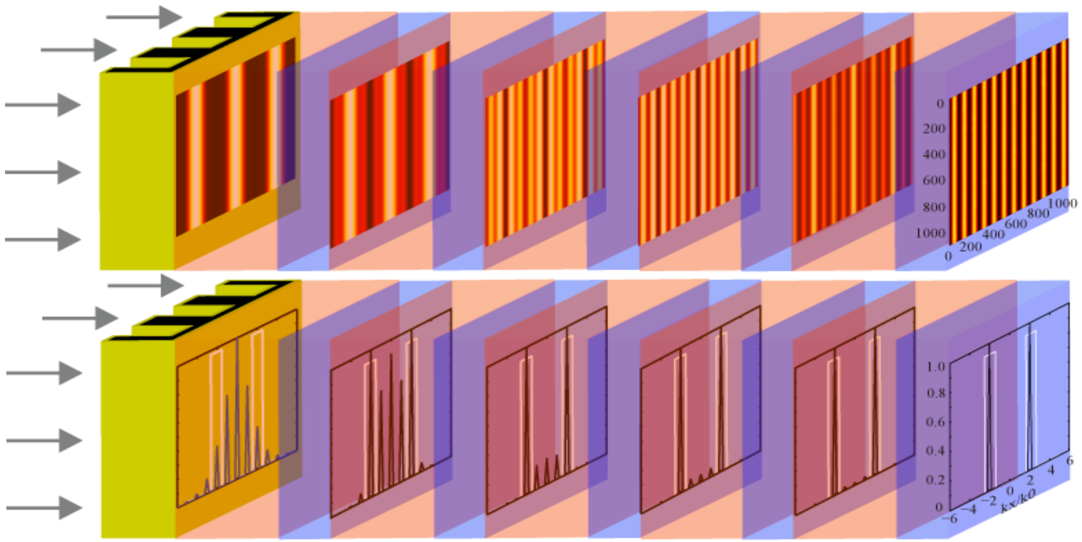
Design Principles

❑ Spatial frequency selection → single high-*k*



X. Chen, et al. ***ACS Nano*** *2016, 10(4): 4039*

- Narrow OTF passband
- Single order diffraction waves transmitted
- Interference with selected evanescent waves



G. Liang, et al., Adv. Opt. Mater. 2015, 3: 1248–1256

- Super resolution
- Increasing contrast
- Improving uniformity

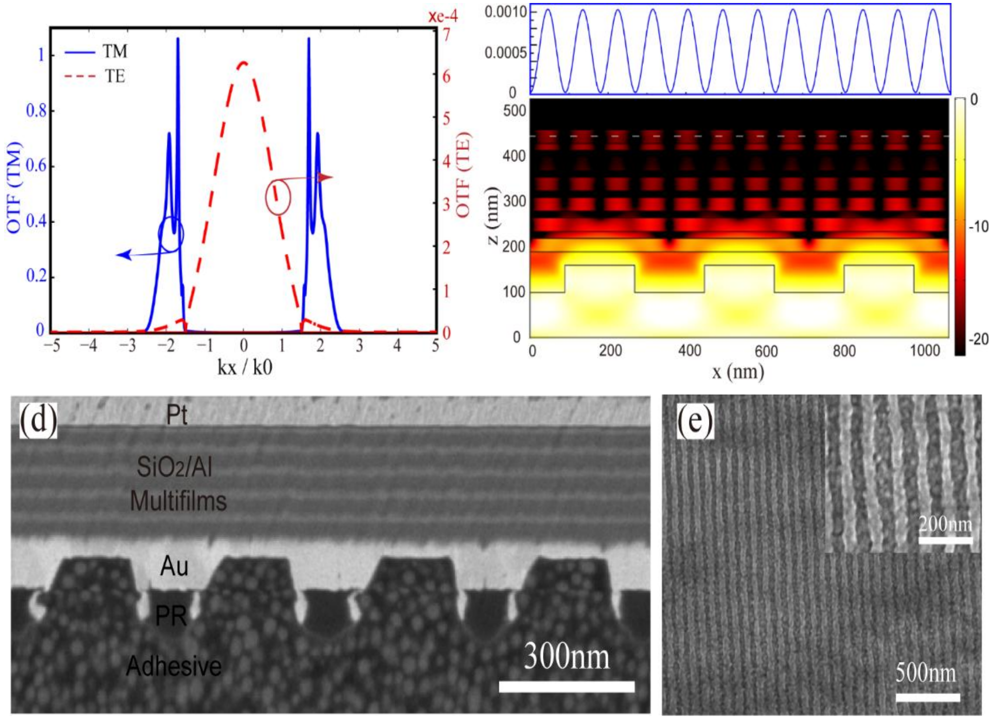
1) Hyperbolic metamaterials

❑ Interference lithography with two SPP beams

- ➢ TM polarized light illuminating the linearly grating mask
- ➢ The ±2 order diffracted waves are filtered through the HMM multilayers

- Linewidth: 45 nm (i.e. less than 1/8 of the light wavelength)
- Period: 90 nm (i.e. 1/4 of the grating mask)
- Depth: 30 nm (i.e. 1:1.5 aspect ratio)

✓ High Contrast



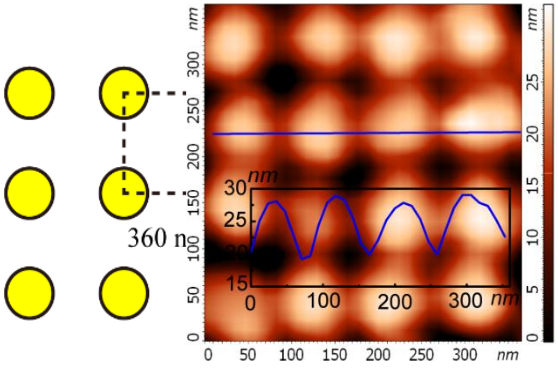
G. Liang, et al., Adv. Opt. Mater. 2015, 3: 1248–1256

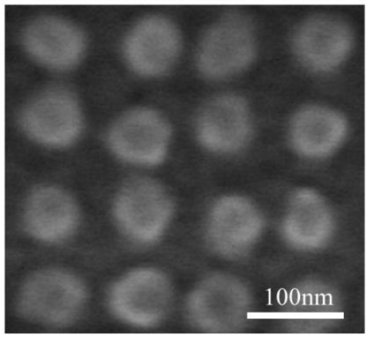
1) Hyperbolic metamaterials

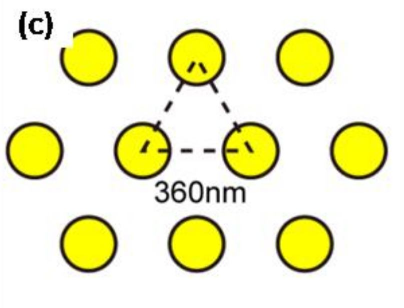
❑ Interference lithography with multiple SPP beams

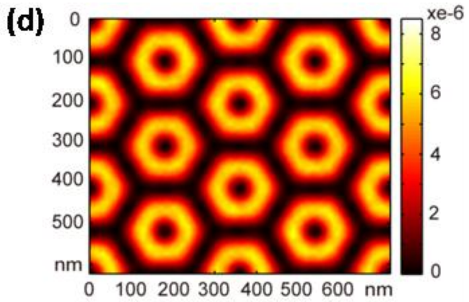
- ➢ Circularly polarized light illuminating the dots grating mask
- ➢ The ±2 order diffracted waves are filtered through the HMM multilayers

- Dot size: 45 nm (i.e. less than 1/8 of the light wavelength)
- Period: 90 nm (i.e. 1/4 of the grating mask)
- Depth: 30 nm (i.e. 1:1.5 aspect ratio)
- Periodic, quasi-periodic, non-periodic patterns could be formed





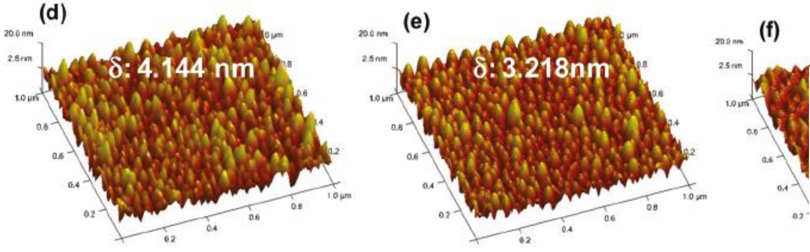




G. Liang, et al., Adv. Opt. Mater. 2015, 3: 1248–1256
G. Liang, et al., IEEE 3M-NANO conference 2016, 331

1) Hyperbolic metamaterials

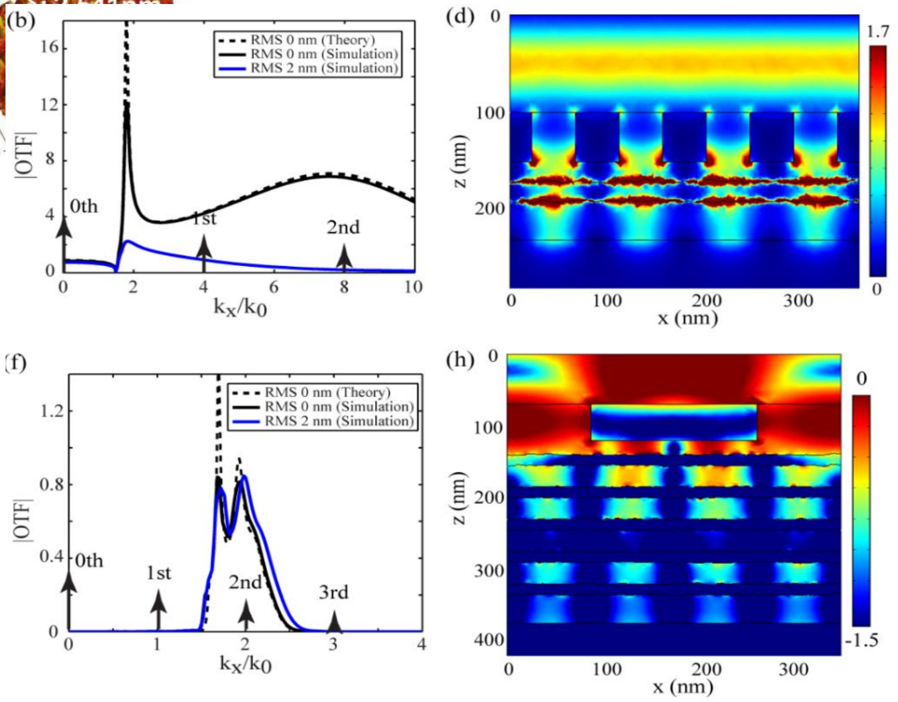
- ☐ HMM system → Spatial frequency selection → Immune to the imperfections



Rough films

E. S. Leong, ***ACS Appl. Mater. Inter.*** *2011, 3: 1148*

✓ High Uniformity



G. Liang, et al., Nanophotonics 2018, 7(1): 277-286

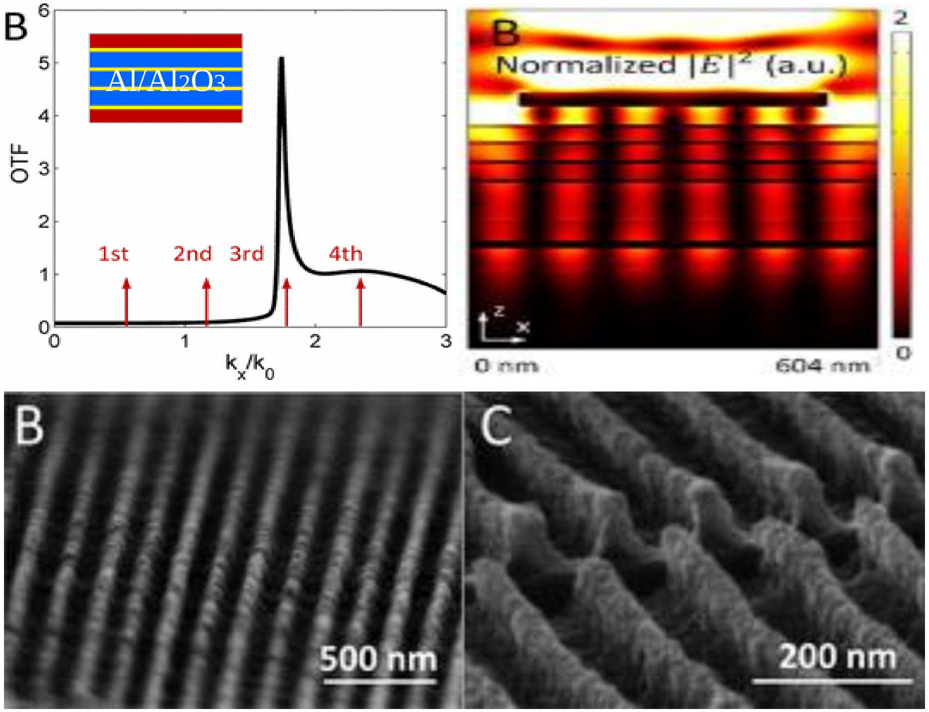
2) Epsilon-near-zero metamaterials

❑ Interference lithography with two SPP beams

- ➢ Higher transmittance, narrower passband
- ➢ The ±3 order diffracted waves are filtered through the ENZ multilayers

- Linewidth: 58.5 nm (i.e. less than 1/7 of the light wavelength)
- Period: 117 nm (i.e. 1/3 of the grating mask)
- Depth: 100 nm (i.e. ~2:1 aspect ratio)

✓ Enough Depth



X. Chen, G. Liang, et al., ACS Nano 2017, 11: 9863-9868

3) Photonic crystal

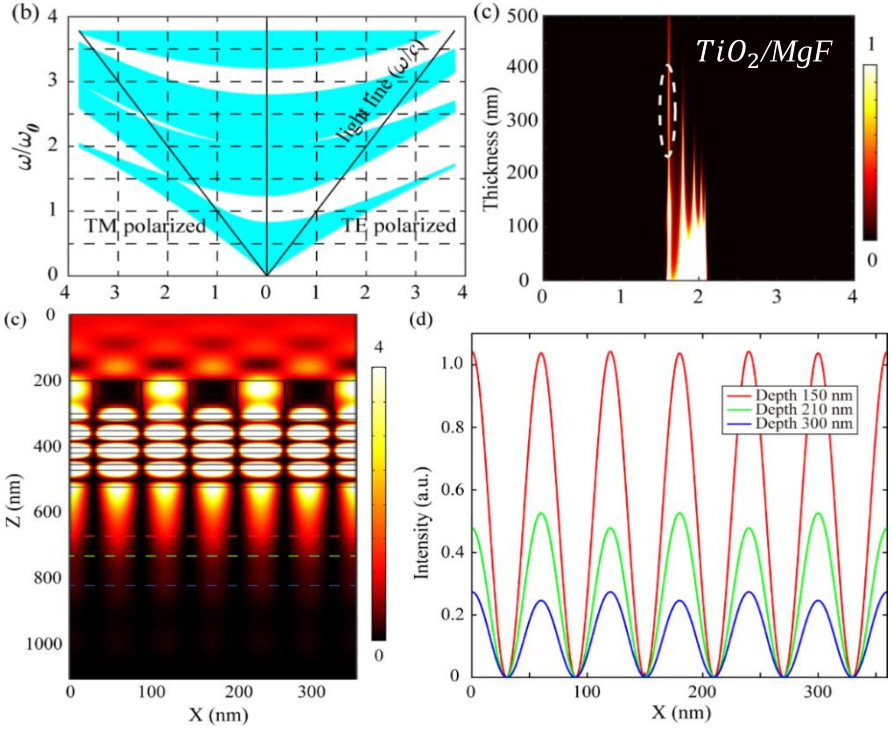
❑ Interference lithography with two evanescent waves

- ➢ Dielectric multilayers with narrow OTF passband
- ➢ The ±1 order diffracted waves are filtered through the PC multilayers

- Linewidth: 30 nm (i.e. less than 1/6 of the light wavelength)
- Period: 60 nm (i.e. 1/2 of the grating mask)
- Depth: >300 nm (i.e. >10:1 aspect ratio)

✓ Extremely low loss

✓ Great depth



G. Liang, et al., Opt. Lett. 2019, 44: 1182-1185

Conclusion

- Spatial frequency selection is feasible for improving the quality of the patterns
- The optimized multilayers could be used for super-resolution interference lithography
    - Immune to the roughness in the multilayer
    - High transmittance
    - High aspect ratio
    - High contrast

Thank you!

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