UV PHOTONIC INTEGRATED CIRCUITS FOR LABEL-FREE STRUCTURED ILLUMINATION MICROSCOPY AND QUANTITATIVE PHASE IMAGING

Chupao Lin

Supervisors: Prof. Nicolas Le Thomas, Prof. Roel Baets

GHENT UNIVERSITY

imec
embracing a better life

16/03/2023

UV PHOTONIC INTEGRATED CIRCUITS FOR LABEL-FREE STRUCTURED ILLUMINATION MICROSCOPY AND QUANTITATIVE PHASE IMAGING

GHENT UNIVERSITY

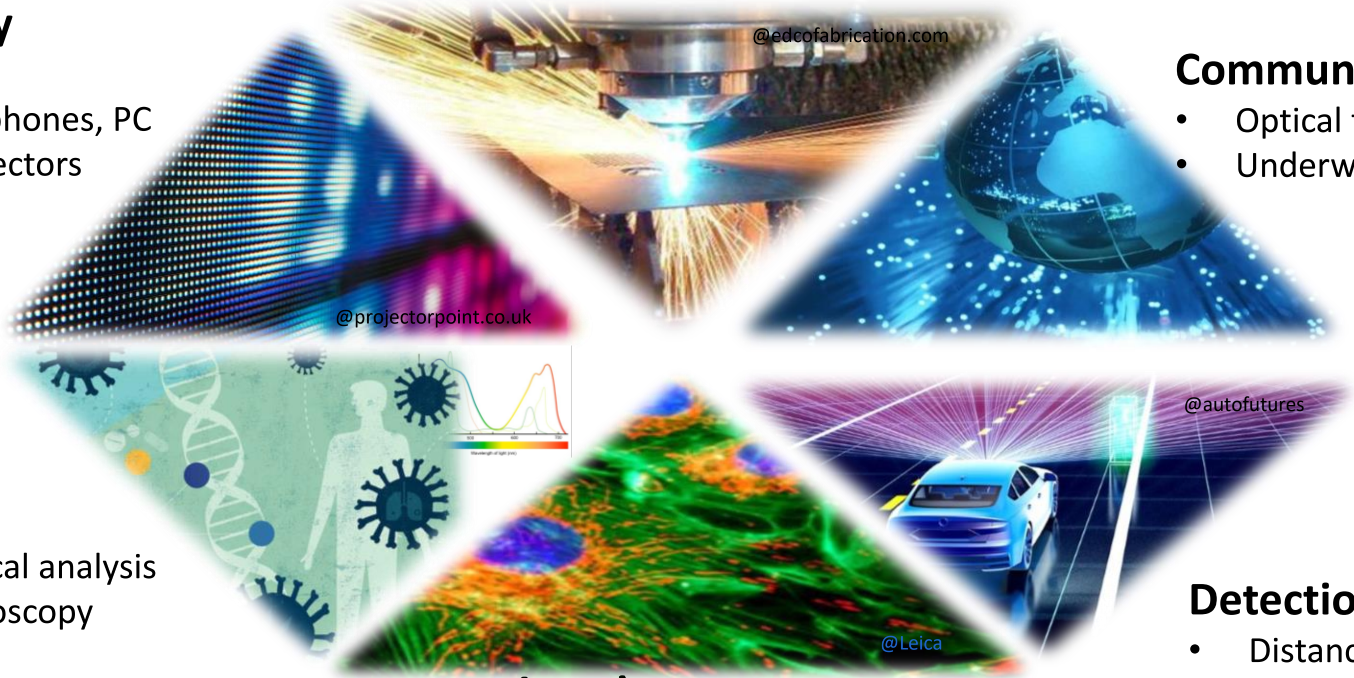
imec
embracing a better life

What is photonics?

Manufacturing
- Laser cutting
- UV lithography

Display
- LED
- TV, phones, PC
- Projectors

Communication
- Optical fiber
- Underwater



Sensing
- Chemical analysis
- Spectroscopy

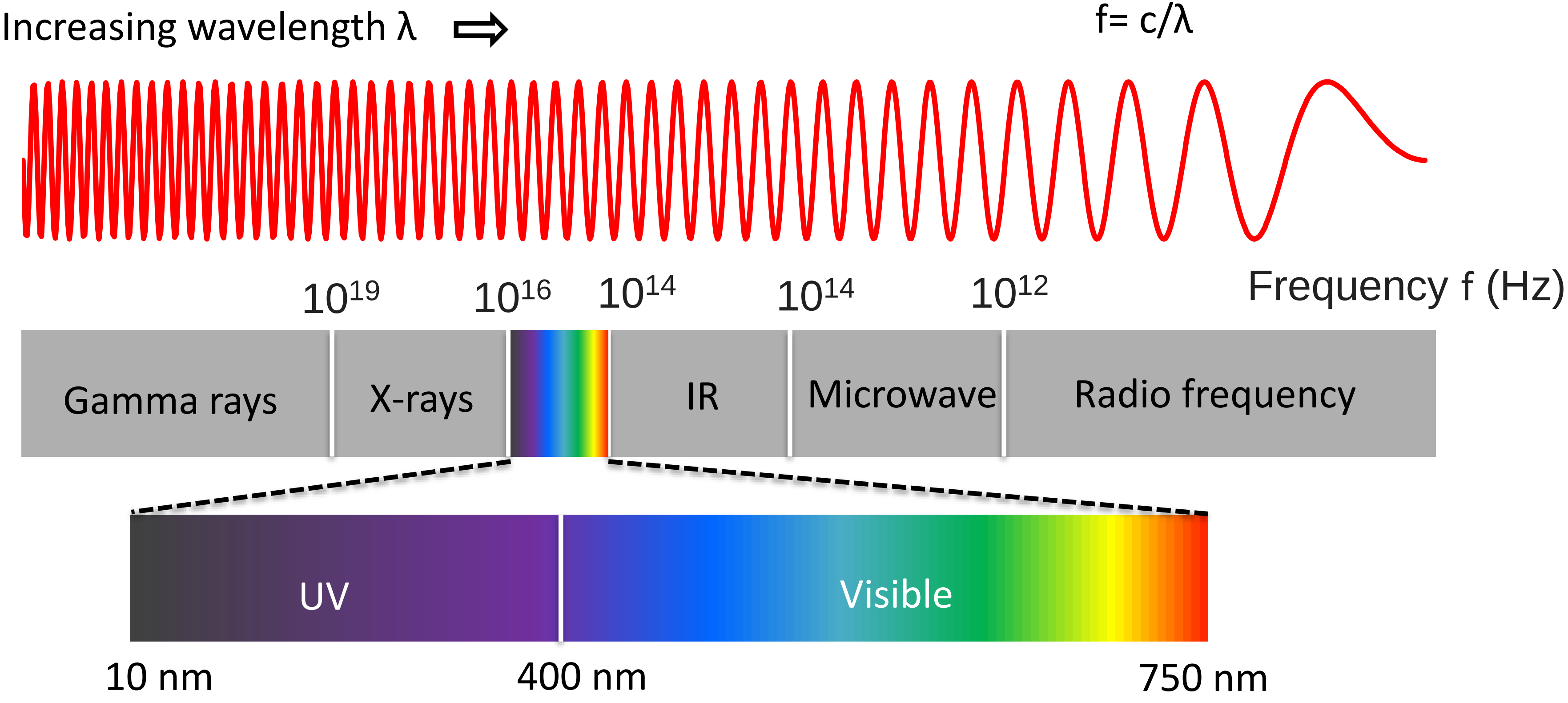
Detection
- Distance measurement
- Lidar

Imaging
- Microscopy
- Telescope

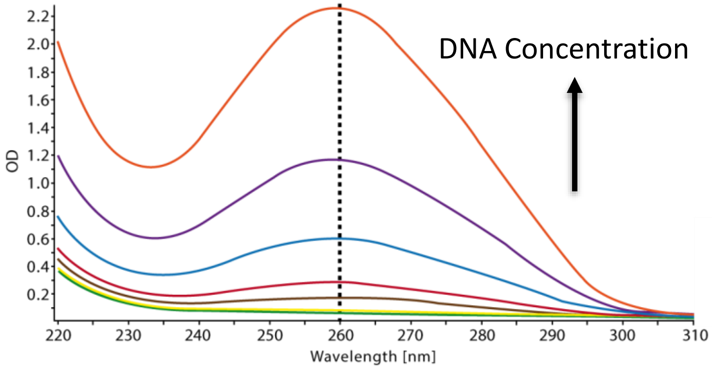
GHENT UNIVERSITY

imec

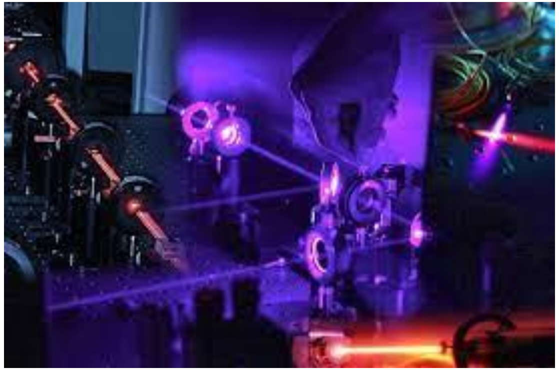
What is light?



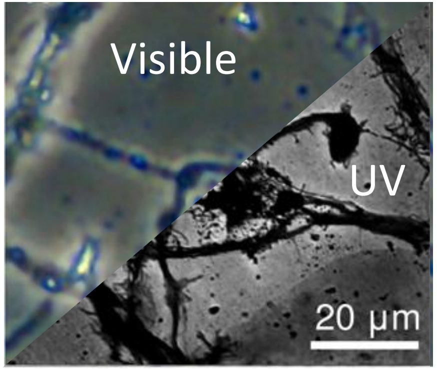
Why UV?



Spectroscopy



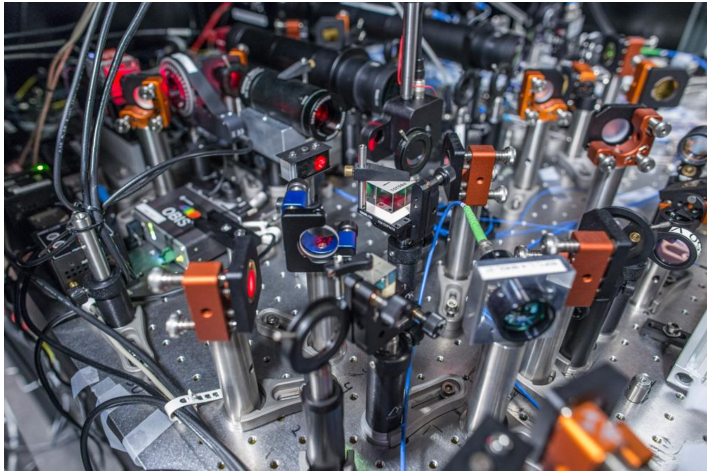
Quantum computing



High-resolution microscopy

GHENT UNIVERSITY imec

Compact solutions for UV beam manipulation?

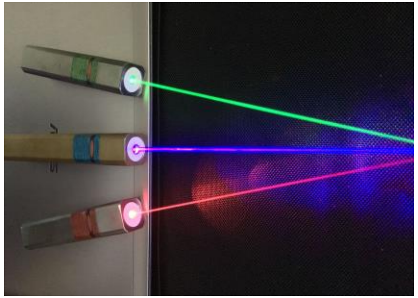


~m

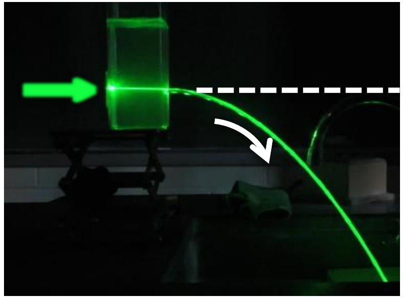
~cm

UV PHOTONIC INTEGRATED CIRCUITS FOR LABEL-FREE STRUCTURED ILLUMINATION MICROSCOPY AND QUANTITATIVE PHASE IMAGING

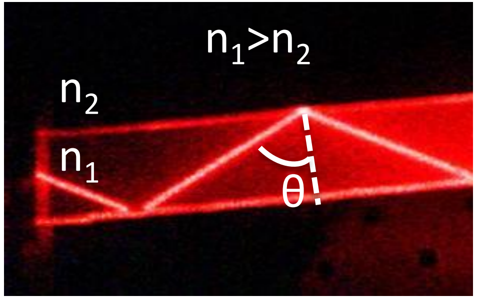
What is Photonic Integrated Circuits (PICs)?



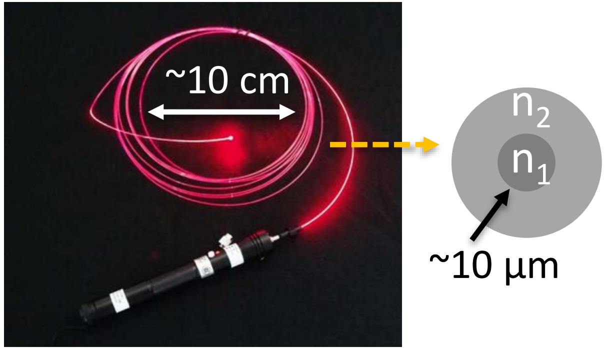
Light travels in a straight-line path



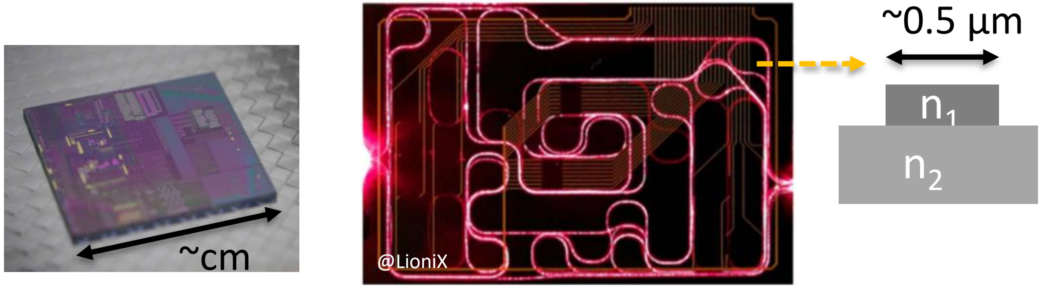
Light guided in water jet



Total internal reflection



Optical fiber

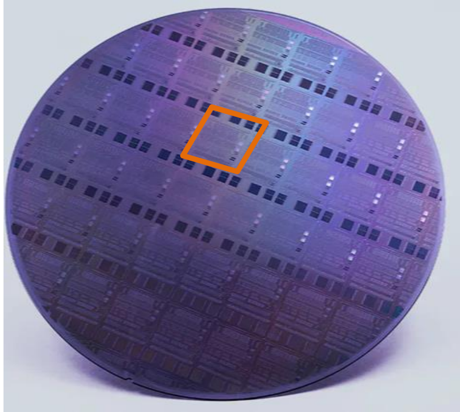


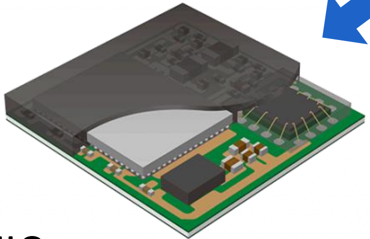
Photonic integrated circuits

GHENT UNIVERSITY imec

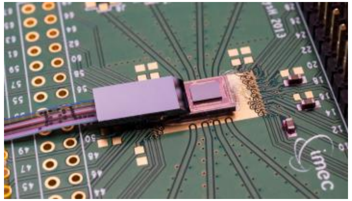
Advantages of Photonic Integrated Circuits

- Low-cost
- Large scale fabrication
- Compact



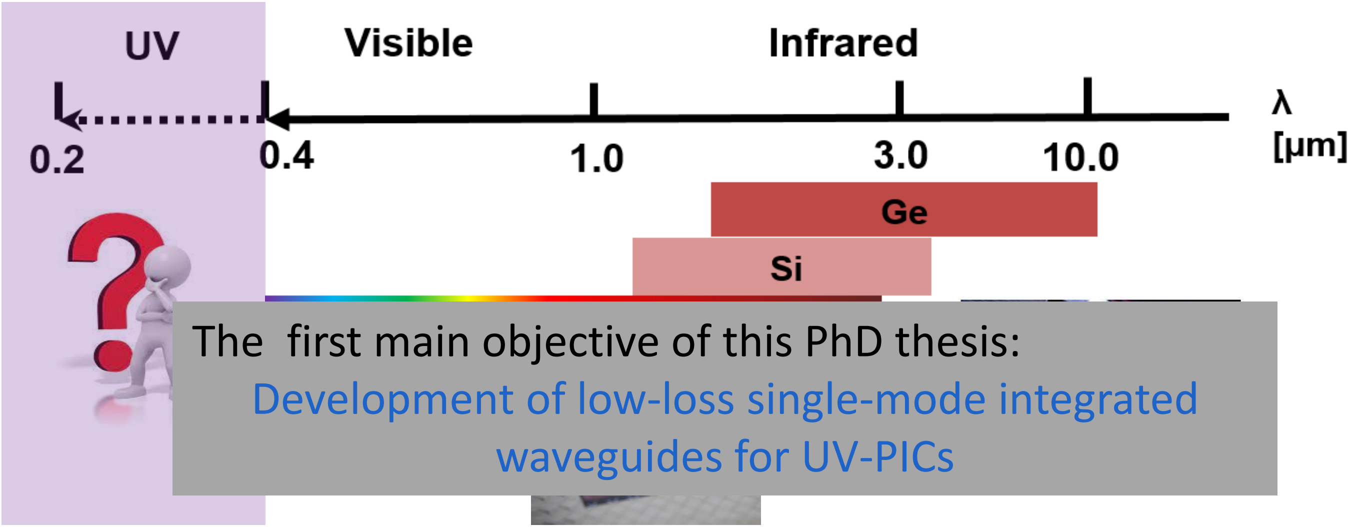


EIC



PIC

CHALLENGES OF UV-PIC PLATFORM



The first main objective of this PhD thesis:
Development of low-loss single-mode integrated waveguides for UV-PICs

- Strong absorption
- High scattering $\propto \lambda^{-4}$

GHENT UNIVERSITY

imec

UV PHOTONIC INTEGRATED CIRCUITS FOR LABEL-FREE STRUCTURED ILLUMINATION MICROSCOPY AND QUANTITATIVE PHASE IMAGING

GHENT UNIVERSITY

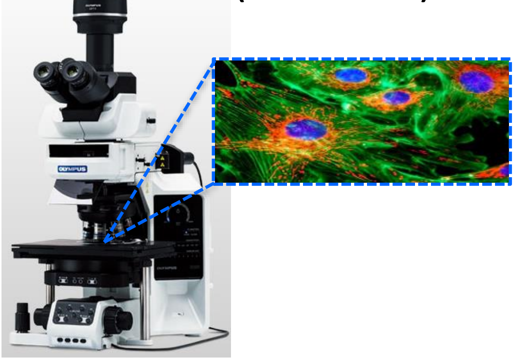
imec
embracing a better life

SEEING THING BETTER WITH OPTICAL MICROSCOPY

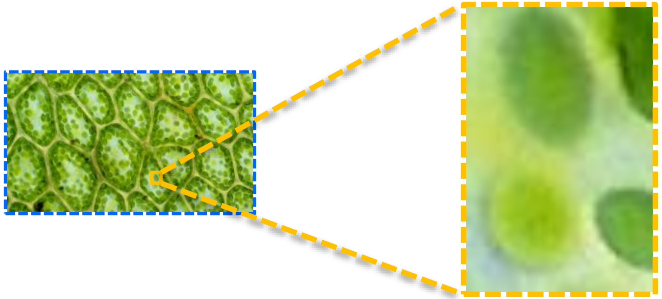
~3x (~0.1 mm)

~10x (~1 µm)

~100x (~200 nm)

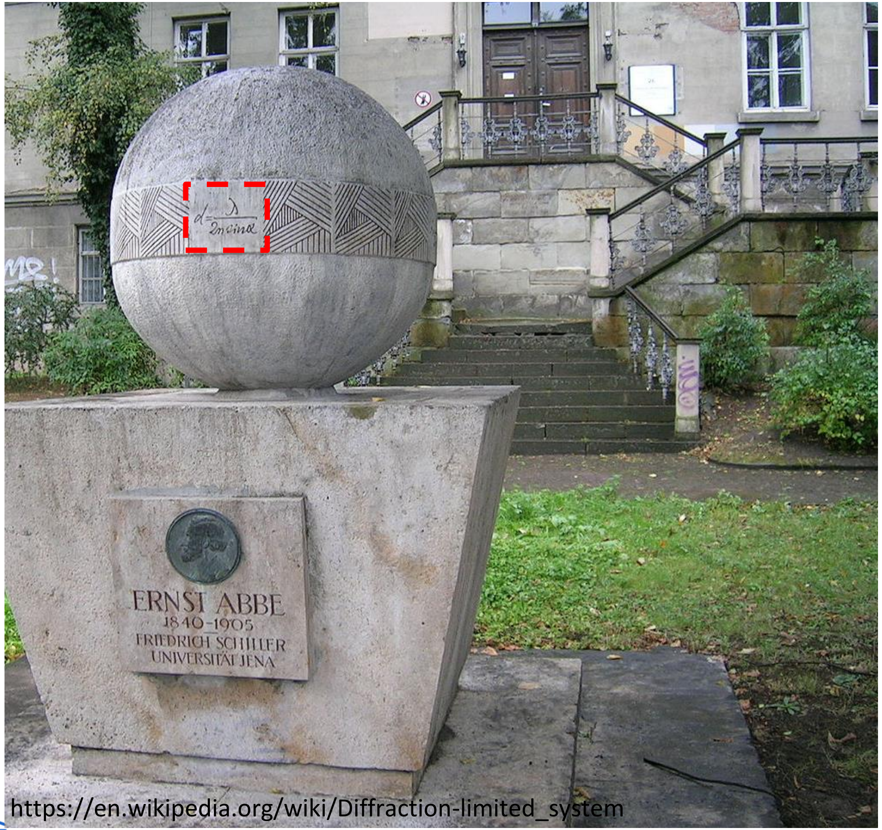


See better with cascaded lenses?



Magnified but blurred

WHAT DETERMINES THE RESOLUTION?



https://en.wikipedia.org/wiki/Diffraction-limited_system

Abbe's resolution limit

$$d = \frac{\lambda}{2nsin(\theta)} = \frac{\lambda}{2NA}$$

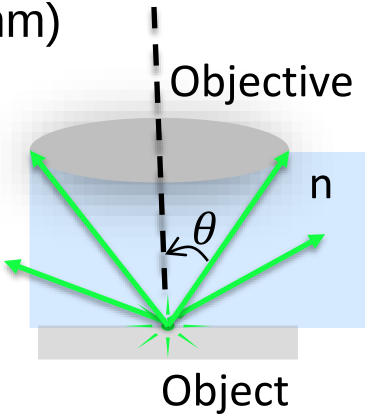
- Wavelength (λ)

  Visible (400 nm-700 nm)

- Refractive index (n)

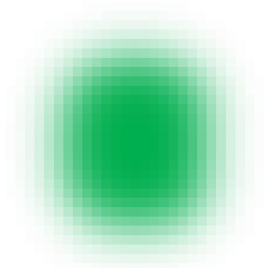
  Air (~1), oil (~1.55)

- Maximum angle (θ)

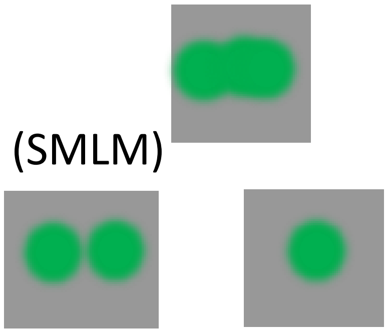


Comparison of Super-Resolution Microscopy Techniques

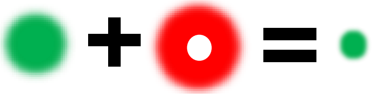
Single fluorophore molecule (~nm)



Imaged fluorescence (~200 nm)



- Single molecular localization microscopy (SMLM)
  - √ high resolution (~10 nm)
  - x Slow (~min), special fluorescent dye
- Stimulated emission depletion microscopy (STED)
  - √ high resolution (~30 nm), fast (~s)
  - x High phototoxicity, complicated optical system

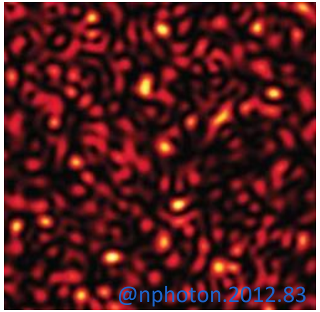


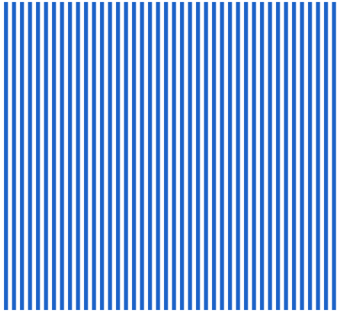
- Structured illumination microscopy (SIM)
  - √ Fast (~s), compatible with conventional dyes
  - x Relatively low resolution (~100 nm)

GHENT UNIVERSITY imec

What is structured illumination?

Speckles

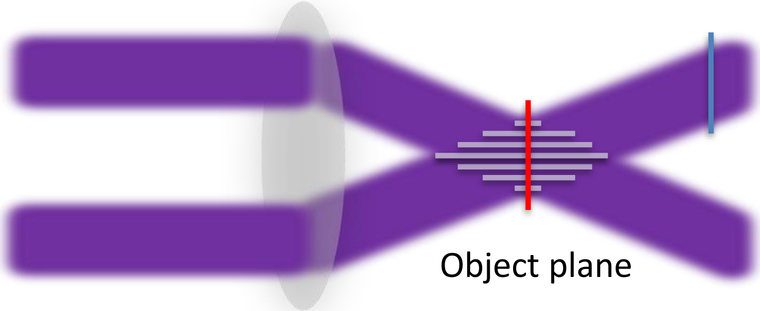




Sinusoidal

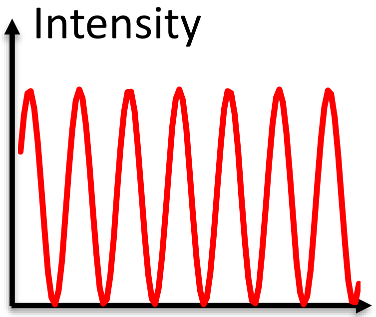
Objective

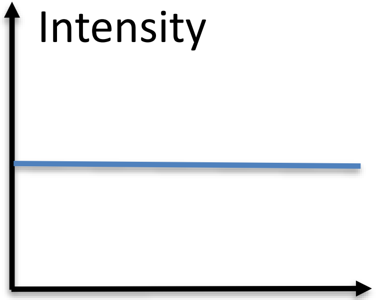
Coherent light



Object plane

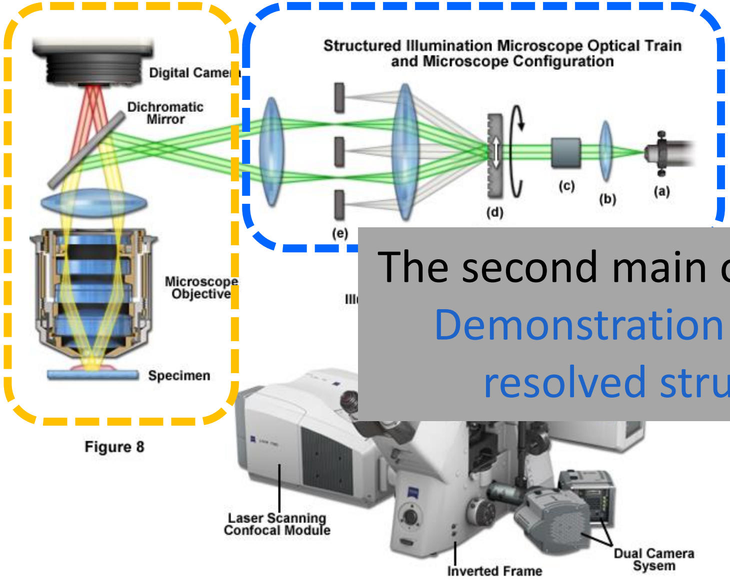
Schematic of two-beam interference





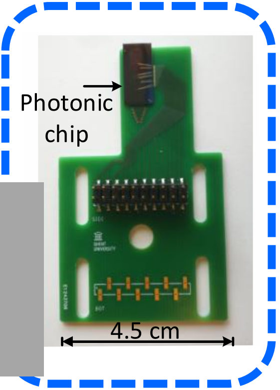
COMPACT, LOW-COST SOLUTION FOR SIM MICROSCOPES

Present SIM microscope configuration



400 nm 700 nm

Our approach using UV-PIC



~5 cm x 5 cm

360 nm

200 nm 400 nm 700 nm

The second main objective of this PhD thesis:
Demonstration of UV-PIC-based label-free super-resolved structured illumination microscopy

[1] https://zeiss-campus.magnet.fsu.edu/articles/superresolution/supersim.html
[2] C. Lin, et al., Nature Communications, 13(1), 4360 (2022)

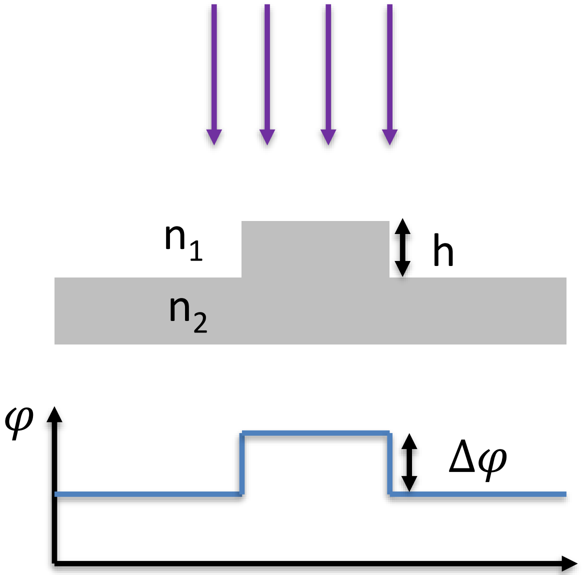
UV PHOTONIC INTEGRATED CIRCUITS FOR LABEL-FREE STRUCTURED ILLUMINATION MICROSCOPY AND QUANTITATIVE PHASE IMAGING

GHENT UNIVERSITY

imec
embracing a better life

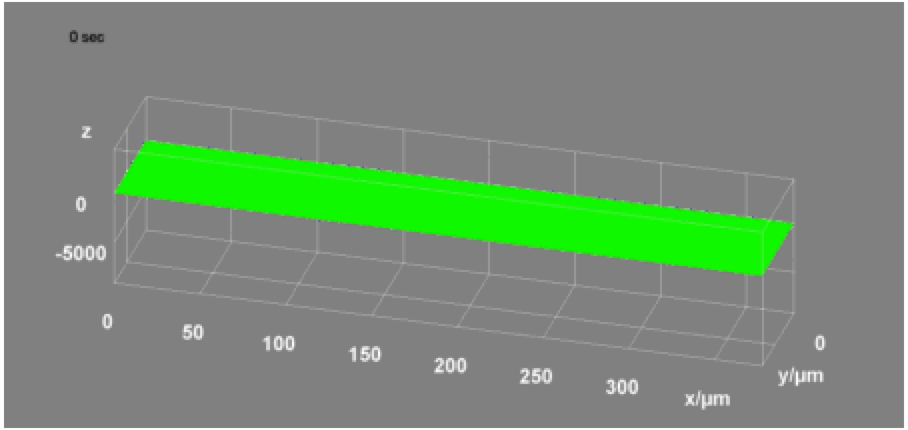
WHAT IS PHASE OF LIGHT?

$$\mathrm{E}(x) = Ae^{i\varphi(x)} = Ae^{i(\frac{2\pi}{\lambda}nx)}$$



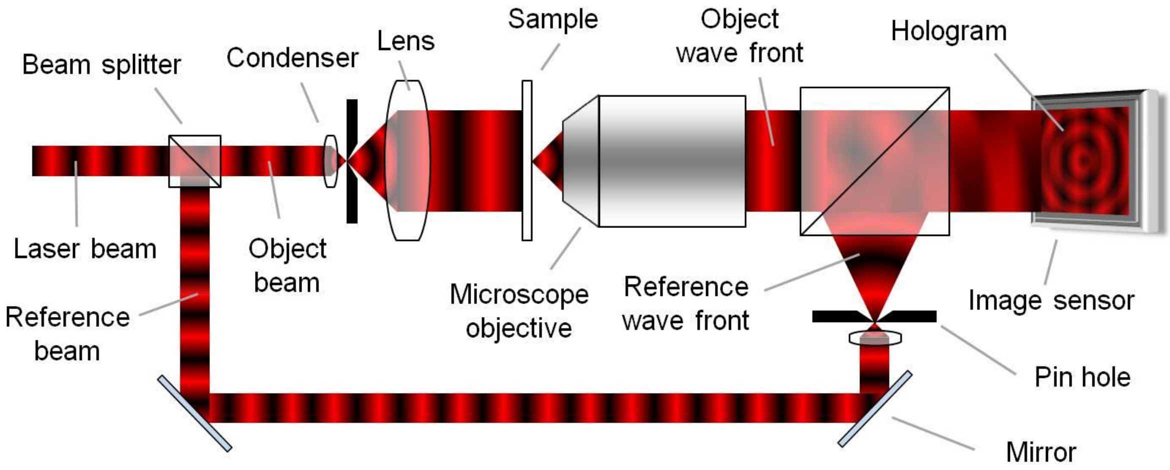
$$\Delta\varphi = \frac{2\pi h(n_2 - n_1)}{\lambda}$$

By knowing the refractive index (n), we can deduce the thickness of the object (h).



Height monitoring during etching

Interferometric based quantitative phase imaging



Phase noise

- Vibration
- Thermal drift

https://en.wikipedia.org/wiki/Digital_holographic_microscopy

Robust intensity-based quantitative phase imaging

Kramers-Kronig relations (Hilbert transform)

$$Z_i = -\frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{Z_r(X)}{(X-x)} dX$$

$$Z_r = \frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{Z_i(X)}{(X-x)} dX$$

Conditions:

1: Causality:

2: Analyticity:

Complex field: $E(x) = A \cdot e^{i(kx+\varphi)}$

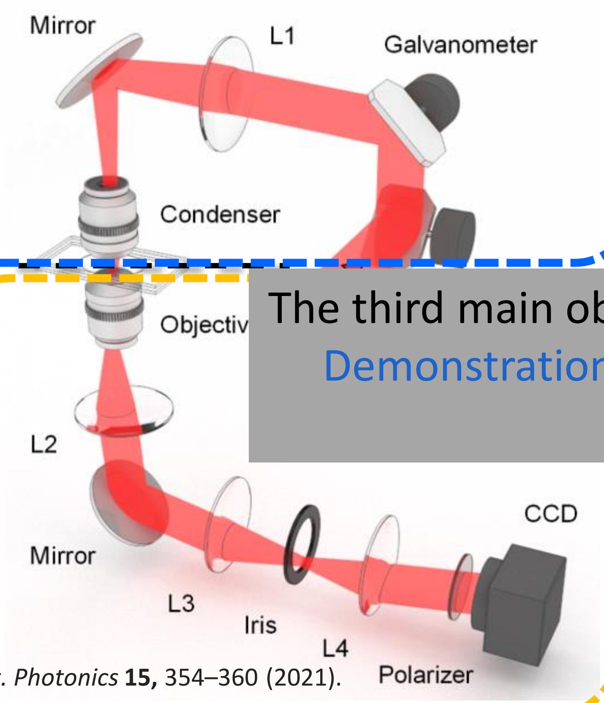
Intermediate function $\chi(x) = \ln\big(E(x)\big) = \ln(A) + i(kx+\varphi)$

Imaginary: $\chi_i = kx + \varphi$ → Phase

Real: $\chi_r = \ln(A)$ → Amplitude

COMPACT, LOW-COST SOLUTION FOR KK-BASED QPI

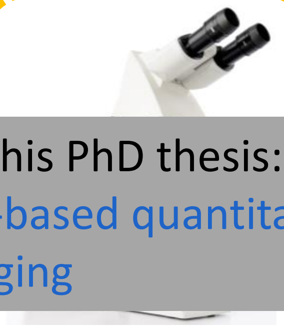
Illumination

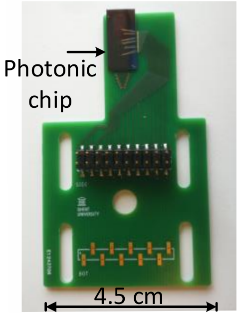


Nat. Photonics **15,** 354–360 (2021).

Configuration of the KK-based QPI technique

Our approach using UV-PIC

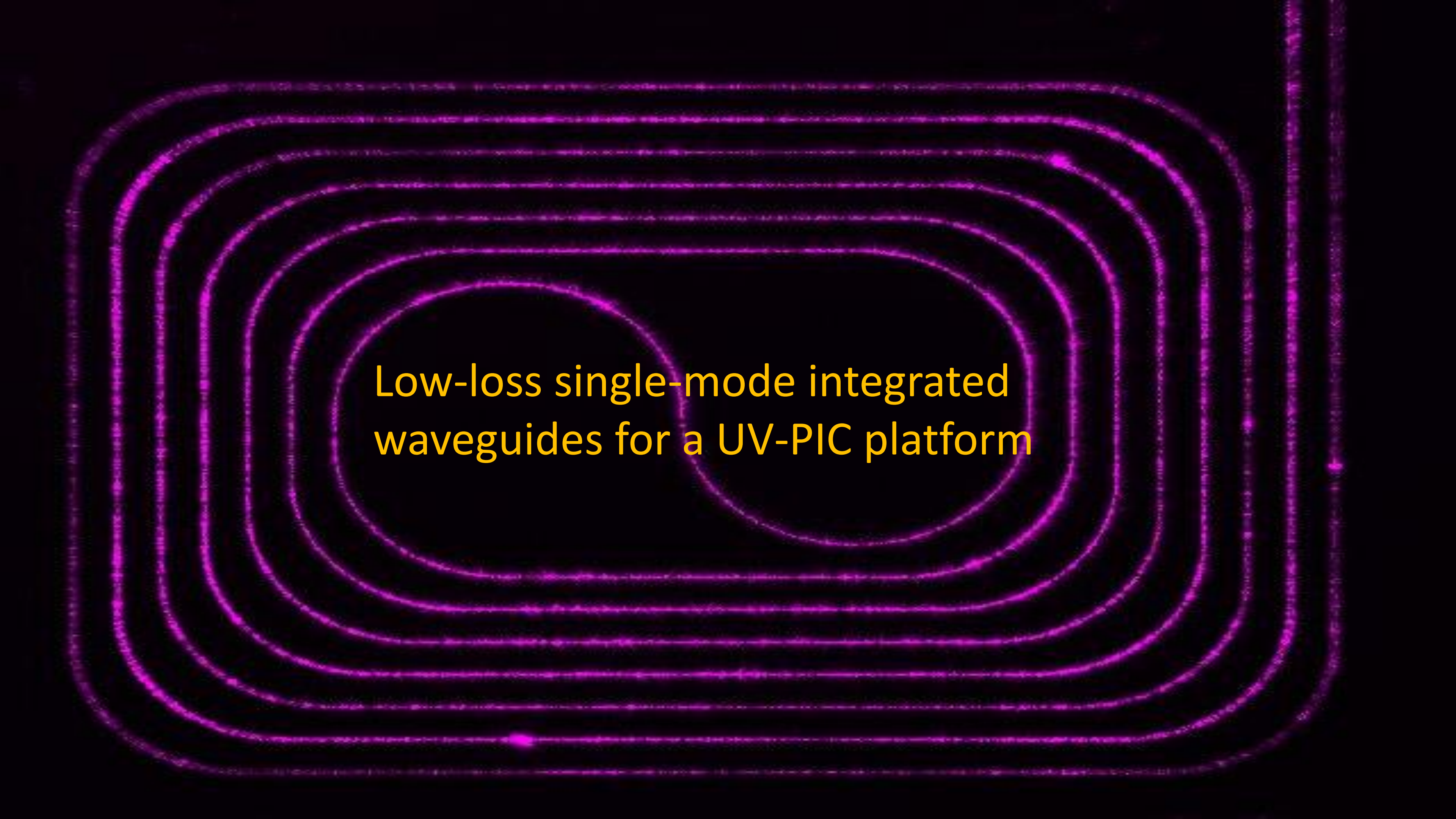




The third main objective of this PhD thesis:

Demonstration of UV-PIC-based quantitative phase imaging

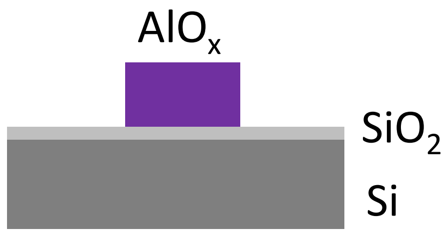
GHENT UNIVERSITY


Low-loss single-mode integrated
waveguides for a UV-PIC platform

STRATEGIES TO PROCESS ALO$_X$ WAVEGUIDE

Deposition

ALD-AlO_x @150 °C →



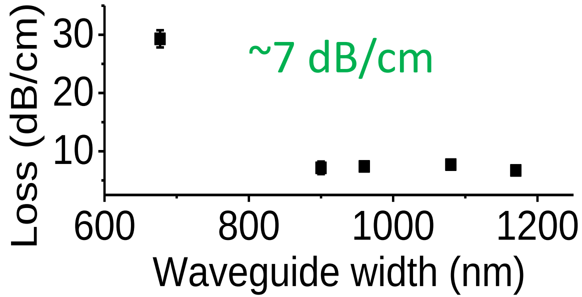
Waveguide cross-section

High purity

ALD-AlO_x @300 °C ←

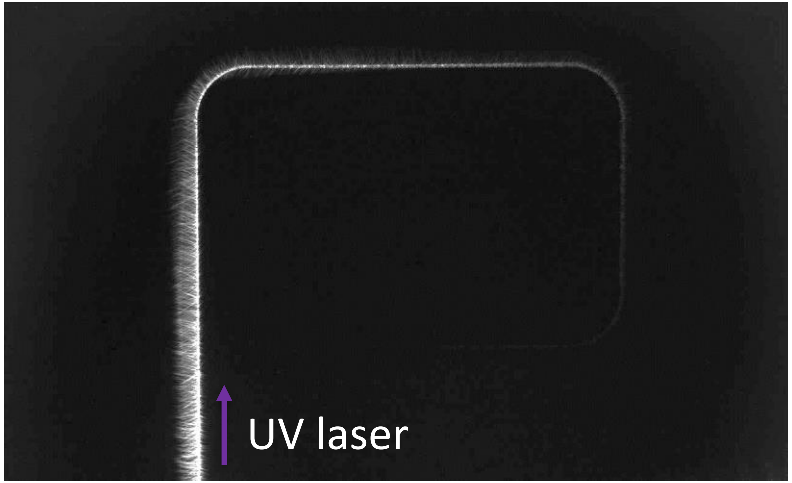
Etching

- **Etching rate**
  Fluorine based → *Chlorine* based
  (3~4 nm/min → ~50 nm/min)
  Nonvolatile AlF_3 ↓
  volatile $AlCl_3$ ↑
- **Etching selectivity**
  Photoresist mask → *SiN_x mask*
  (~0.1→ ~1.5)
- **Etching quality**
  Gas mixture BCl_3→ $BCl_3/Cl_2/Ar$
  (loss)
  BO_x ↓
  $BClO_x$ ↑

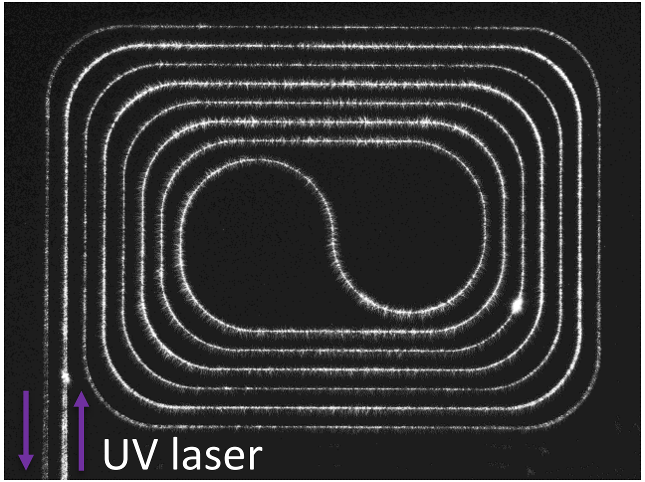


Clear improvement of waveguide fabrication

UV light propagation in spiral waveguides with a total length of 2.7 cm



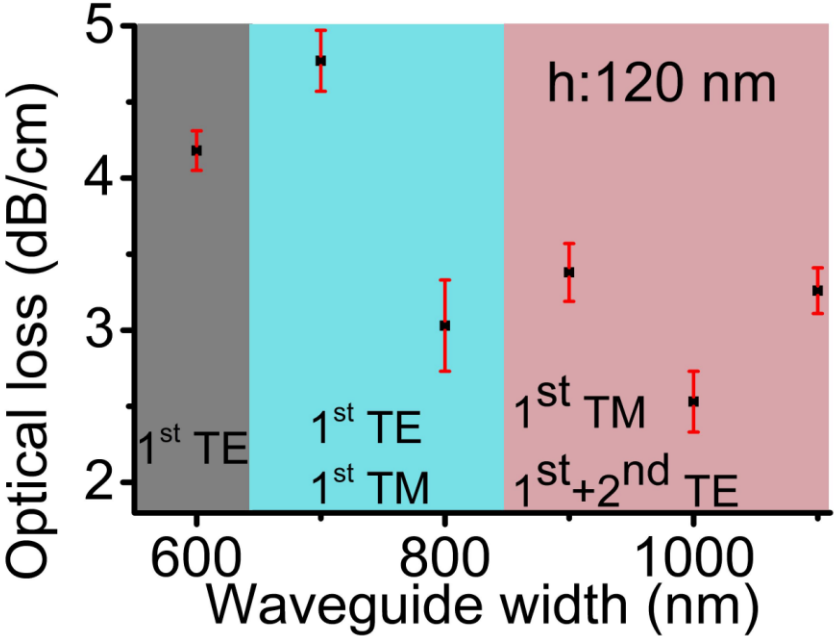
Before optimization

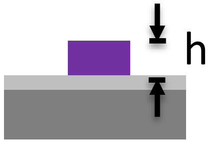


After optimization

GHENT UNIVERSITY imec

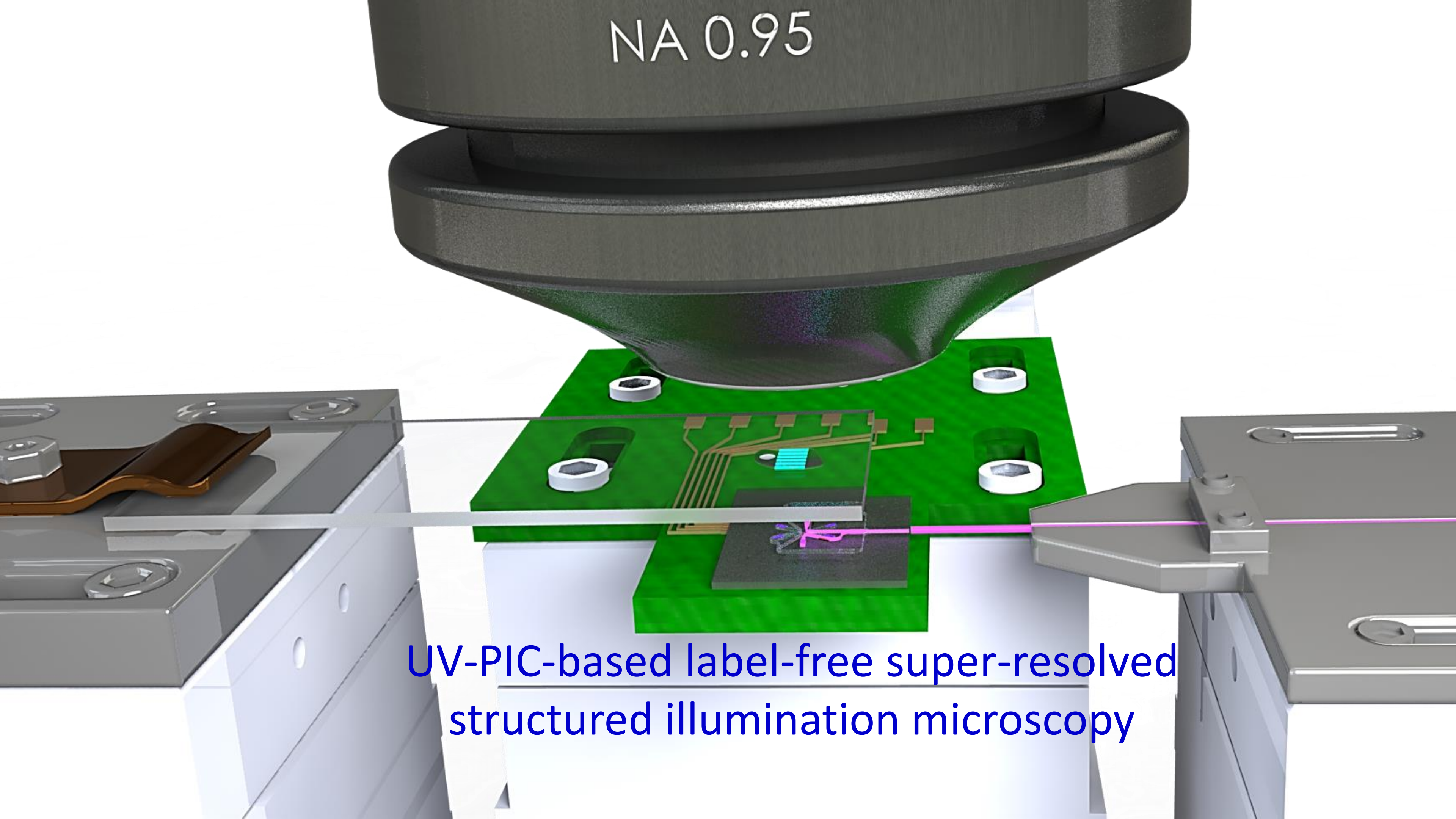
3 dB/cm at a wavelength of 360 nm





Relationship between the waveguide width and waveguide loss

C. Lin, et al., JSTQE, 29(4), p.1-9,2022



UV-PIC-based label-free super-resolved structured illumination microscopy

UNVEILING PRINCIPLE OF SIM WITH A UV PIC

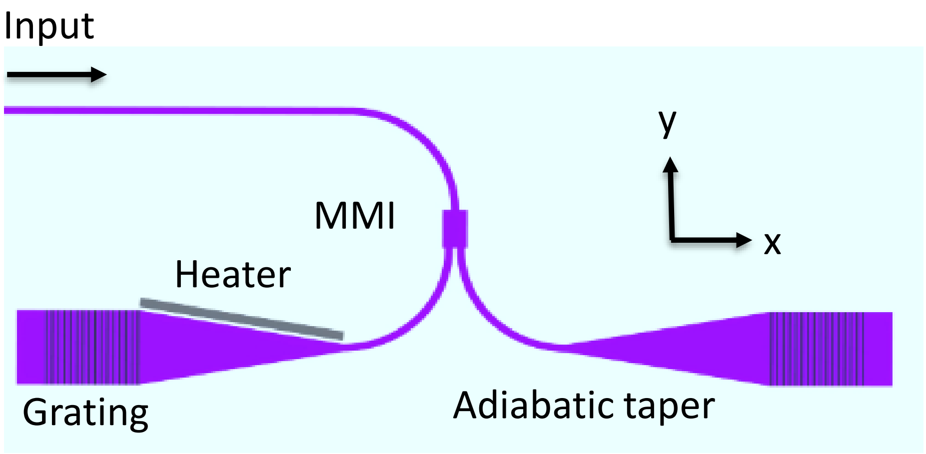
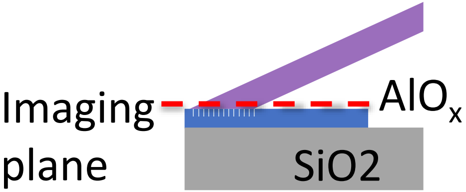


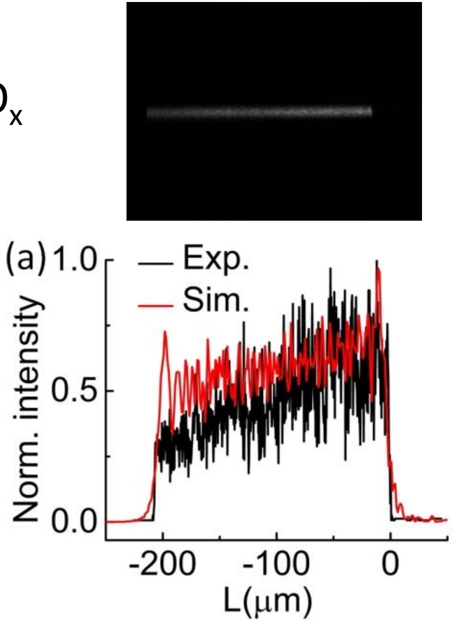
Diagram of UV-PIC for 1D structured illumination

GHENT UNIVERSITY imec

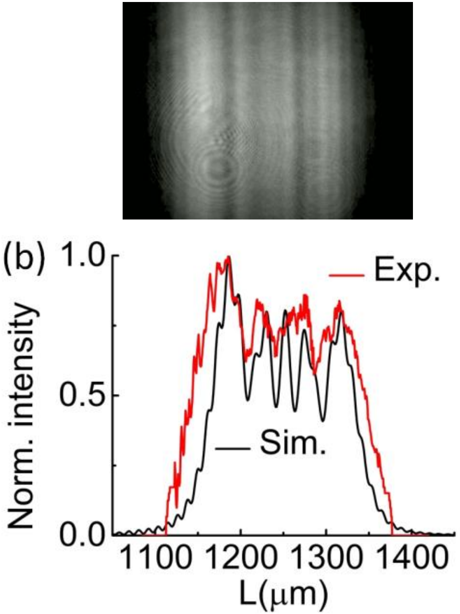
C. Lin, et al., JSTQE, 29(4), p.1-9,2022

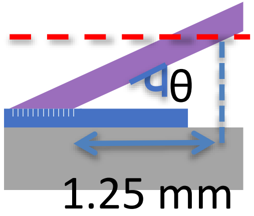
UV BEAM WITH A LARGE FIELD OF VIEW





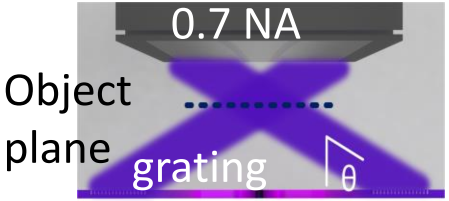
FOV 170 μm x 200 μm

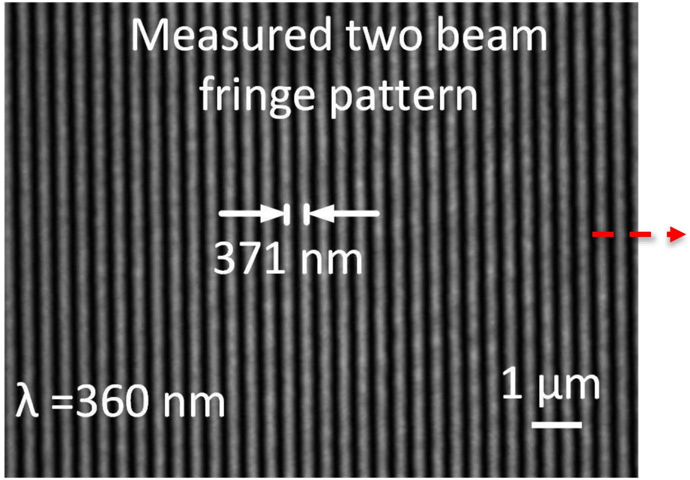


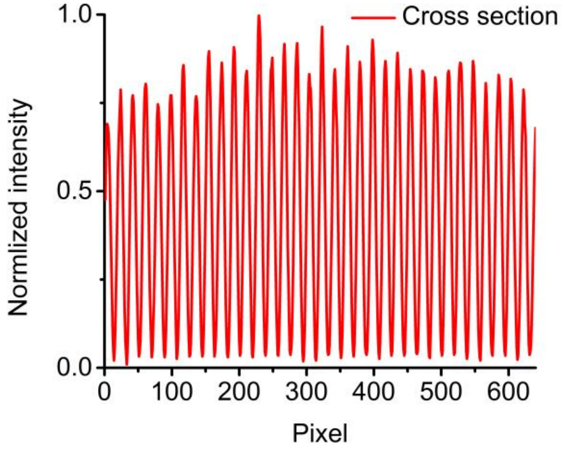


Beam profile at near field (left) and far field (right), θ=11.7°

High visibility of fringe pattern







UV two beam interference fringe pattern, $\theta = 29^{o}$

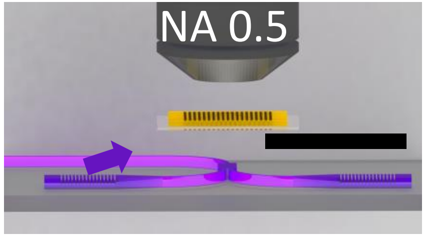
High Visibility up to 0.93

GHENT UNIVERSITY imec

C. Lin, et al., JSTQE, 29(4), p.1-9,2022

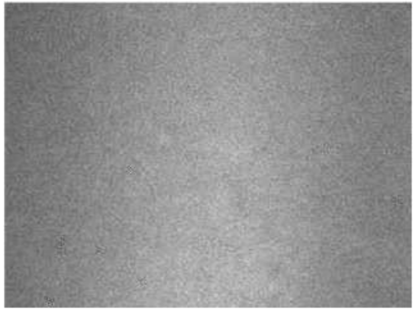
DEMONSTRATION OF CHIP-SIM ON 1D OBJECT

Grating pitch G=300 nm < optical resolution 585 nm

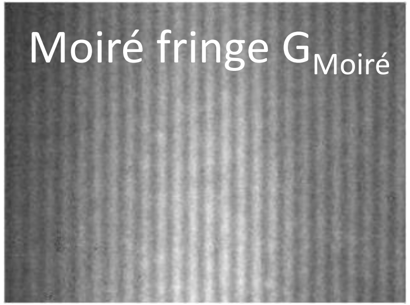


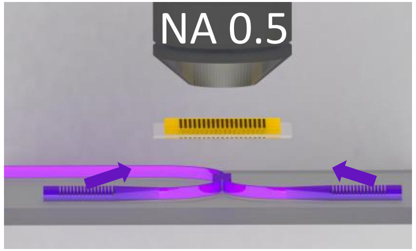
Real space

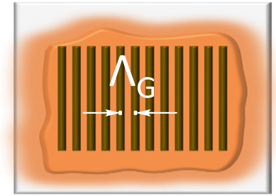
Uniform illumination



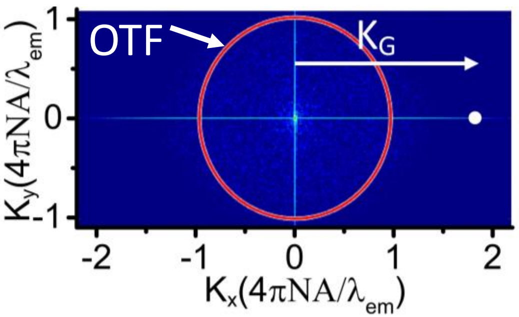
Structured illumination

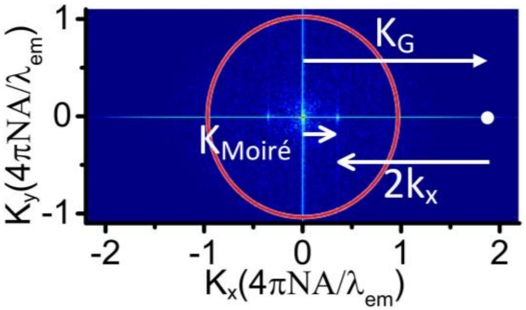






Fluorescent object

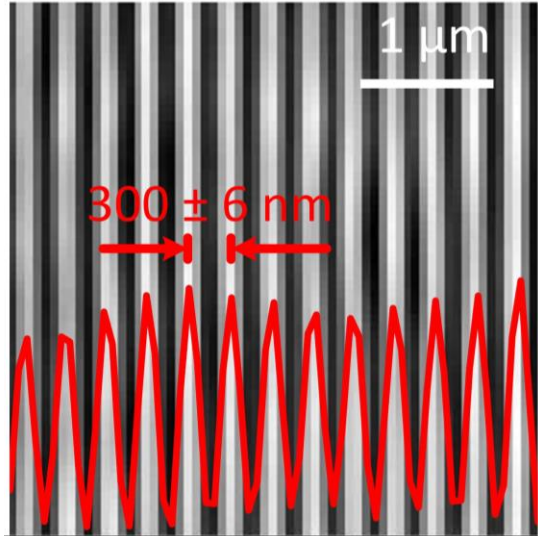




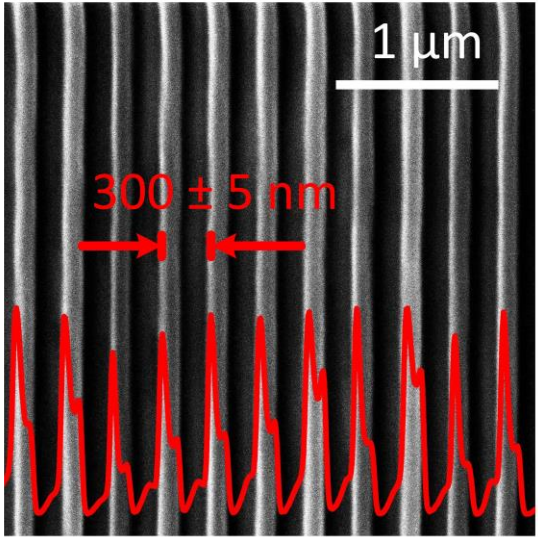
Fourier space

C. Lin, et al., JSTQE, 29(4), p.1-9,2022

Resolution enhancement checked by SEM



SIM image of dye filled groove

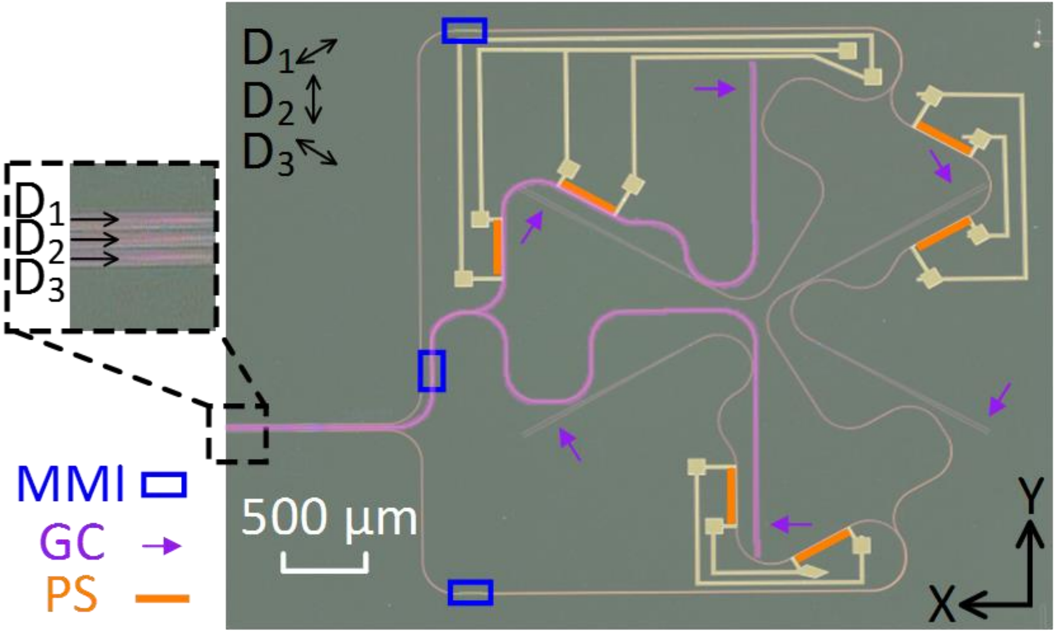


SEM image of metal lines

Super-resolution SIM using photonic chip is demonstrated on 1D object

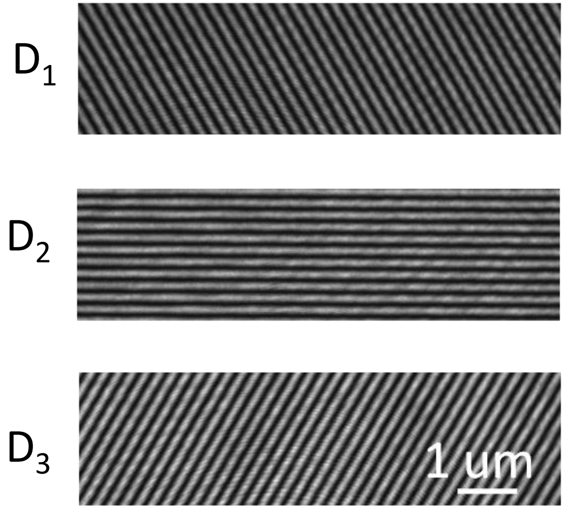
GHENT UNIVERSITY imec

CIRCUITS DESIGN FOR STRUCTURED ILLUMINATION



Optical image of the fabricated UV-PIC

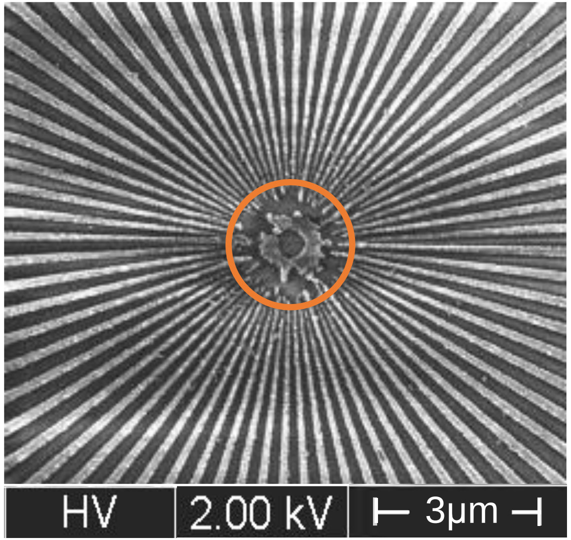
Visibility>0.9



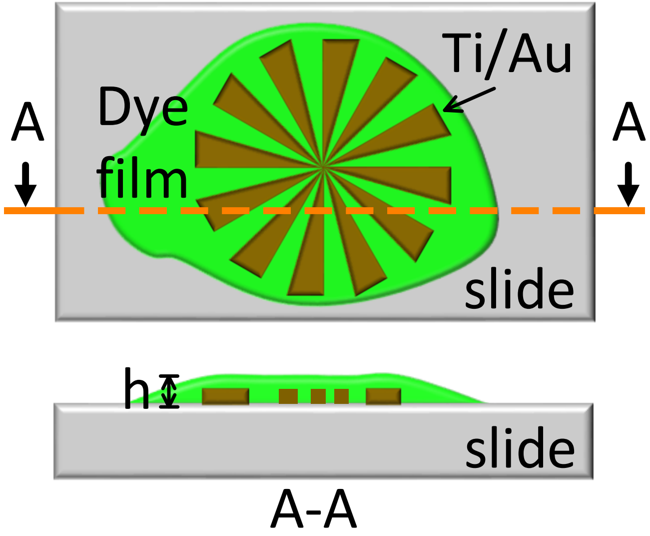
Optical images of the profiles of the generated structured illumination

C. Lin, et al., Nature communication, 13(1), p.1-9,2022

QUANTIFYING THE PERFORMANCE OF PIC-BASED SIM



SEM image of metallic
spoke target



Schematic of fluorescent
spoke target

C. Lin, et al., Nature communication, 13(1), p.1-9,2022

X1.8 TIMES BETTER WITH UV-PIC SIM

WF and SIM image of the spoke target

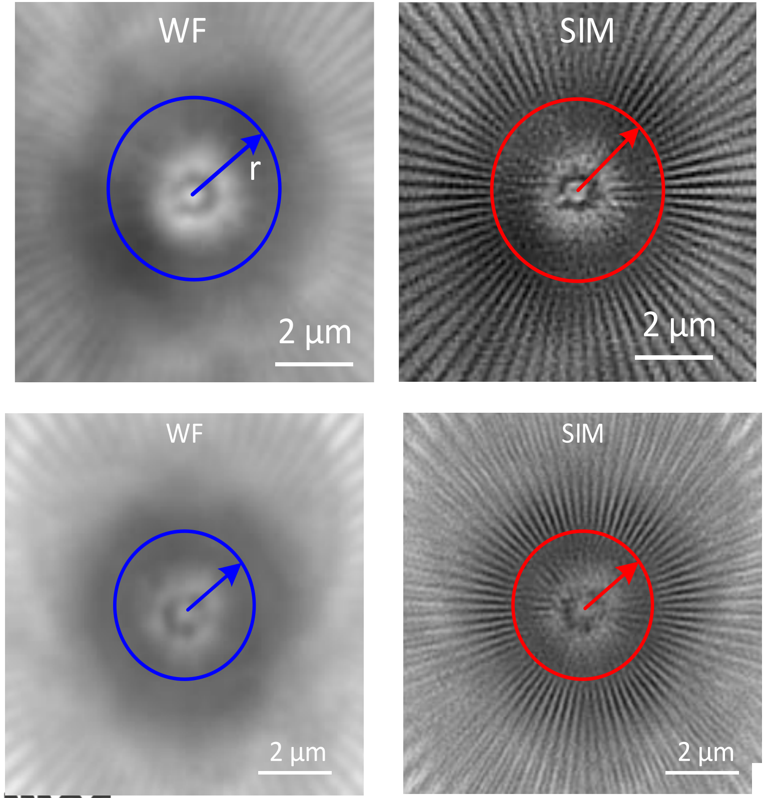
Intensity profile along the circle at r=1.9 µm

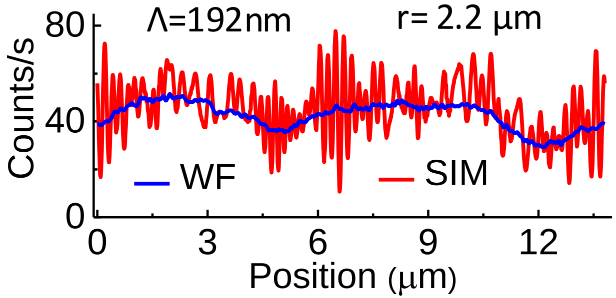
NA_{ex}=0.5

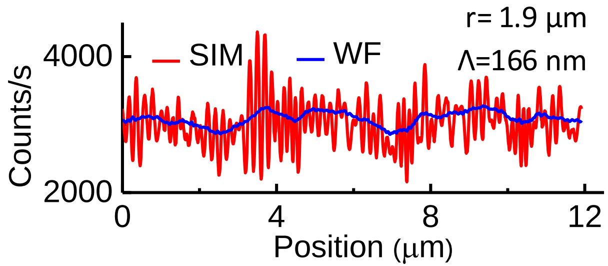
x1.6

NA_{ex}=0.9

x1.8





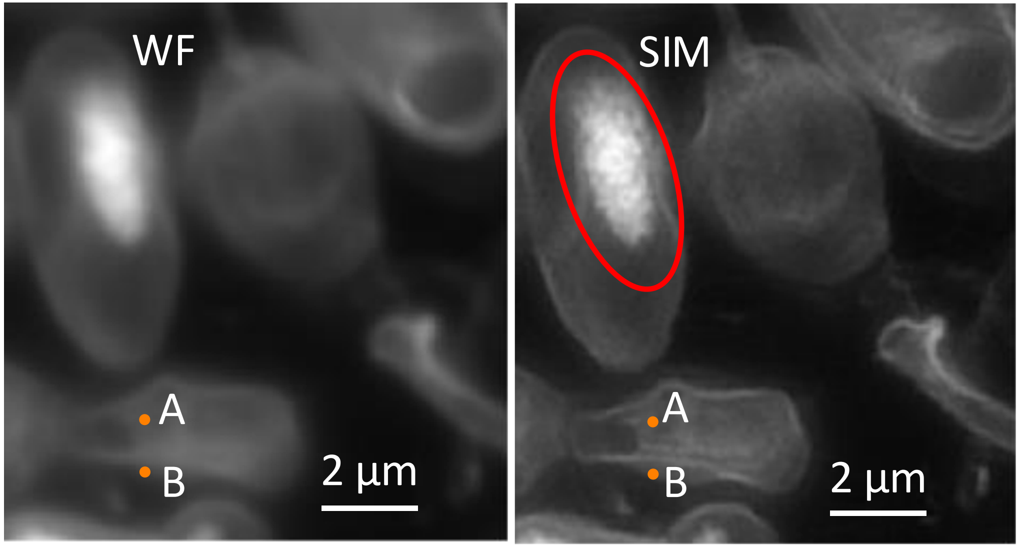


GHENT UNIVERSITY

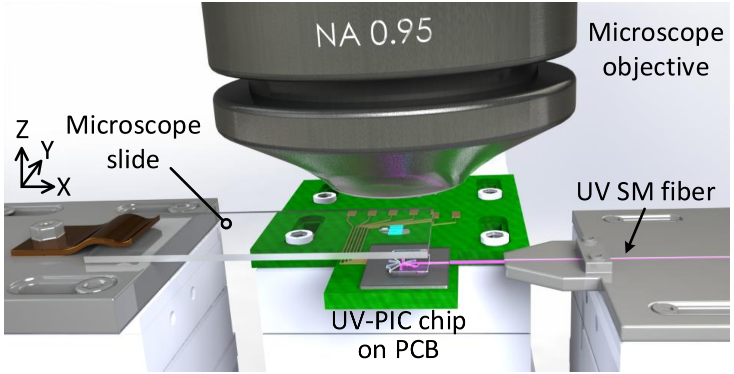
imec

C. Lin, et al., Nature communication, 13(1), p.1-9,2022

SUPER-RESOLVED AUTOFLUORESCENCE IMAGES OF YEAST CELLS



WF and SIM image of yeast cells

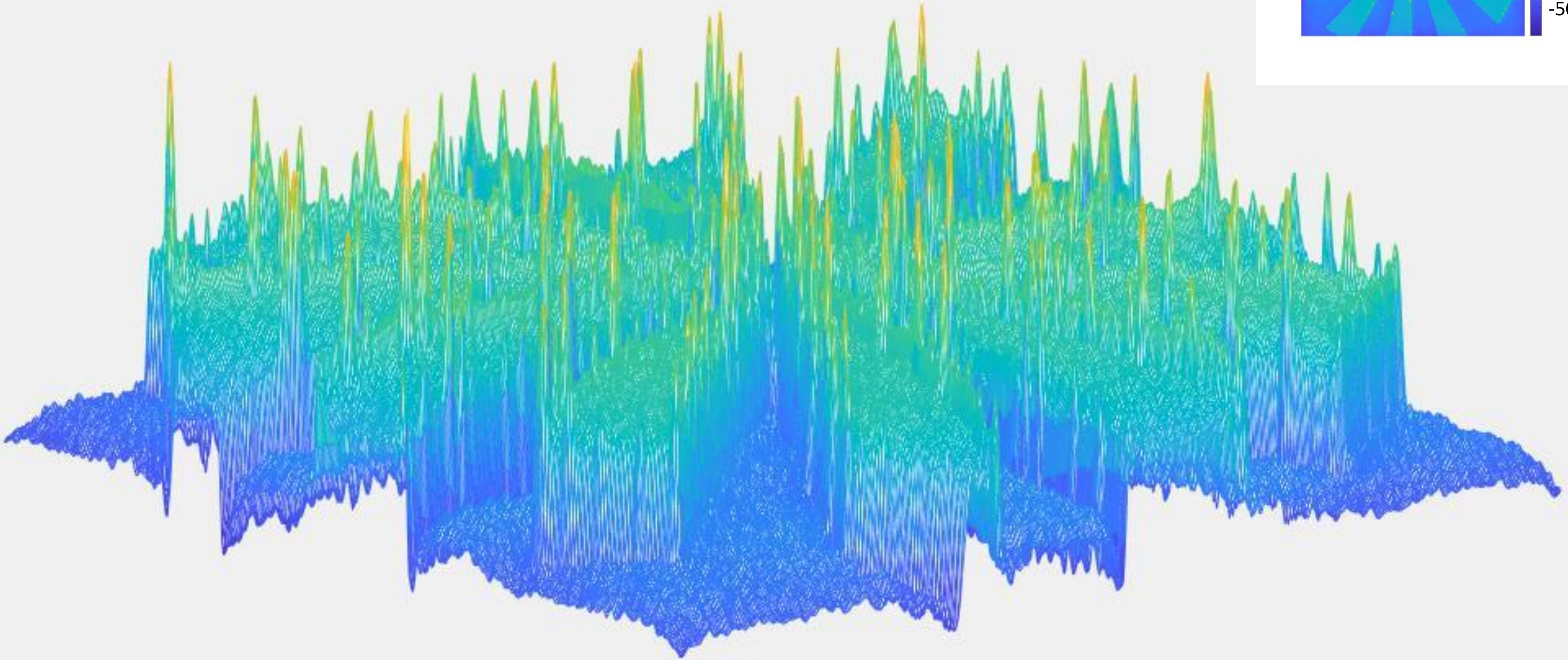


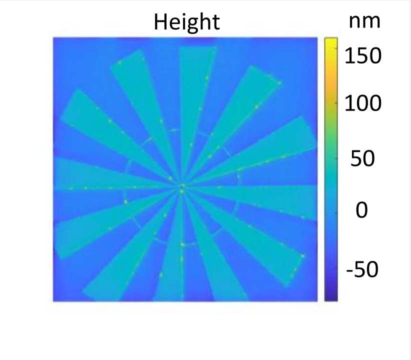
Schematic of the UV-PIC-based SIM technique

Enhancement factor: x1.6

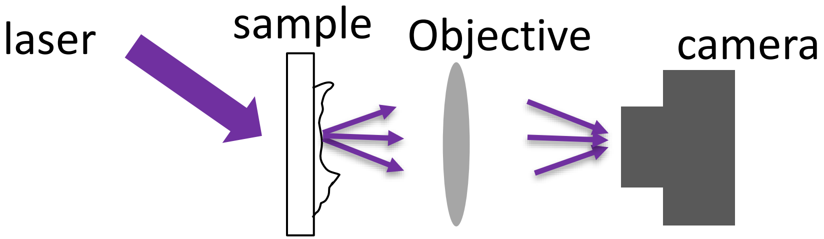
C. Lin, et al., Nature communication, 13(1), p.1-9,2022

UV-PIC-based quantitative phase imaging





Configuration to implement KK-relations



Conditions:

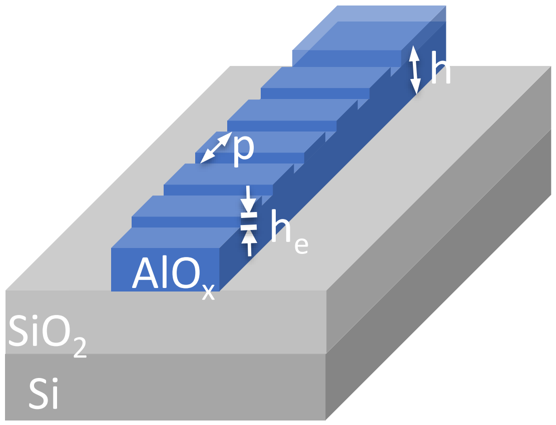
1: Causality:

2: Analyticity:

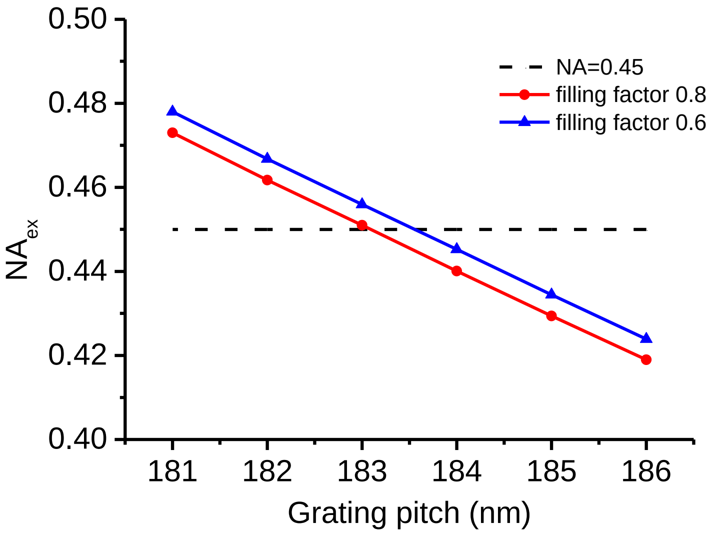
1. Vanish one of the half planes in k-space, $NA_{ex} \geq NA_{co}$
2. Work in bright field condition, $NA_{ex} \leq NA_{co}$

$$NA_{ex} = NA_{co}$$

High accuracy on beam manipulation via UV-PICs



Schematic of grating out-coupler

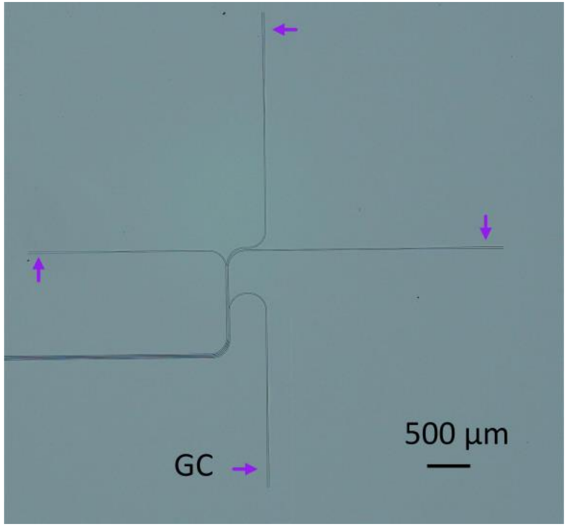


Relationship between numerical aperture NA_{ex} and grating pitch at filling factor of 0.8 and 0.6, respectively.

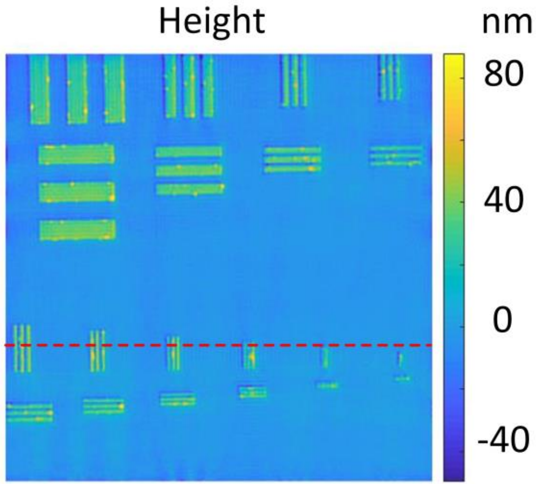
$$\Delta NA_{ex} = 0.005$$

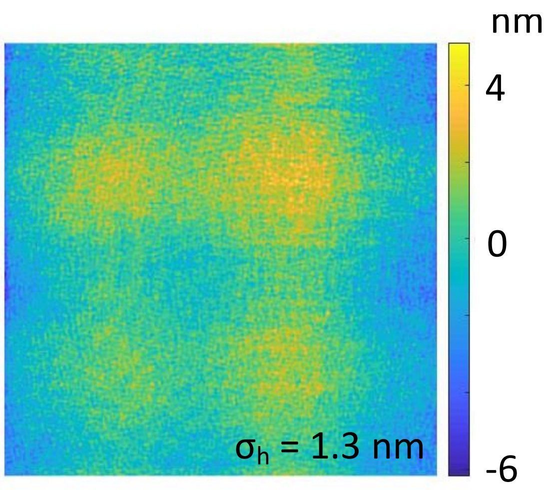
GHENT UNIVERSITY imec

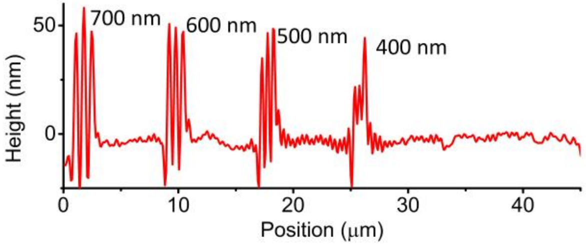
UV-PIC FOR QUANTITATIVE PHASE IMAGING

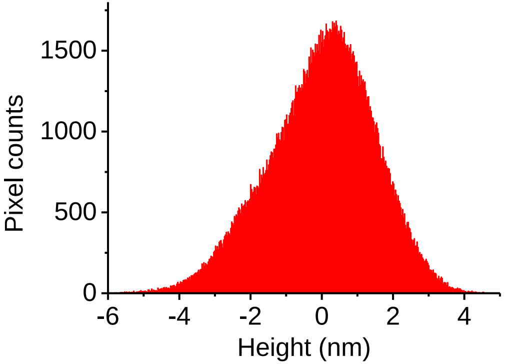


Optical image of fabricated UV-PIC for KK-QPI









C. Lin, et al., CLEO, 2023, accepted

PROSPECTIVES

- Low spatial noise QPI using on-chip switching approach
- Large-field-of-view SIM (0.2 mm→ 0.5 mm)
- UV-PICs for multi-modal advanced microscopy (SIM and QPI)
- AlO_x/SiN_x hybrid platform operating for UV/Vis wavelengths

Q&A

Chupao Lin

PhD candidate

E Chupao.Lin@UGent.be

T

@PhotonicsUGent

@Chupao Lin

Chupao Lin

www.photonics.intec.ugent.be

GHENT UNIVERSITY

imec embracing a better life

FACULTY OF ENGINEERING AND ARCHITECTURE

nb-photonics Center for Nano- and Biophotonics Ghent University