Mid-infrared scanning microscopy with undetected photons

Josué R. León Torres[1,2,3], Vasile-Laurentiu Dosan[1,4,5], Marija M. Ćurčić[6], Oliver de Vries[4], Frank Setzpfandt[1,2], Markus Gräfe[2,7], Valerio Flavio Gili[2]

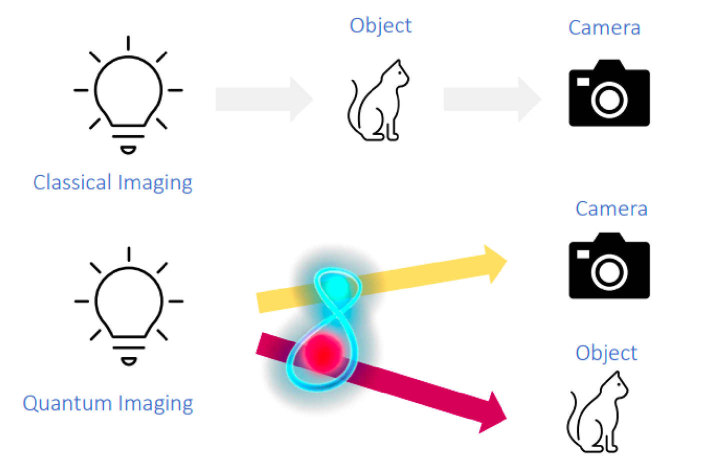
[1] Abbe Center of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Straße 6, 07745 Jena,Germany
[2]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, 07745 Jena, Germany
[3]Cluster of Excellence Balance of the Microverse, Friedrich Schiller University Jena, Jena, Germany
[4]Quantum Optics Jena GmbH, Am Zementwerk 8, 07745 Jena, Germany
[5]Max Planck School of Photonics, Friedrich Schiller University Jena, Albert-Einstein-Straße 15, 07745, Jena, Germany
[6]Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Zemun, Belgrade, Serbia
[7]Institute for Applied Physics, Technical University of Darmstadt, Otto-Bernd-Straße 3, 64287 Darmstadt, Germany

Introduction

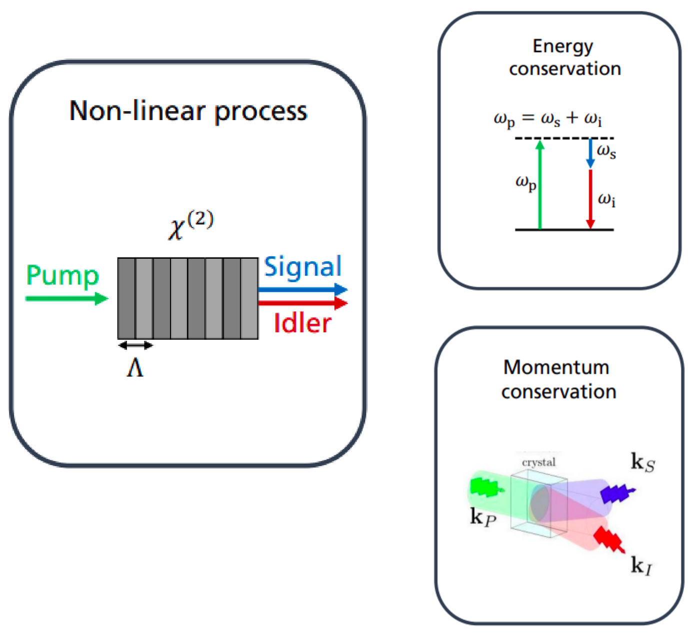
The mid-infrared (MIR) spectral region, spanning from 2- to 25-µm, provides access to rich chemical information through the vibrational modes of functional groups, lipids, and other complex molecules. However, conventional imaging in this range has been limited by difficulties in generating MIR light and by the lack of mature detection technology. Quantum imaging with undetected light (QIUL) [1] offers a solution by employing photon-pair sources, where the sample is illuminated with MIR light while detection and image reconstruction are carried out at visible wavelengths. In this work, we demonstrate a raster-scanning QIUL method that eliminates the dependence on spatial correlations, thereby achieving diffraction-limited resolution and overcoming a fundamental limitation of earlier QIUL schemes.

Undetected photons - concept

- Going around the classical barriers

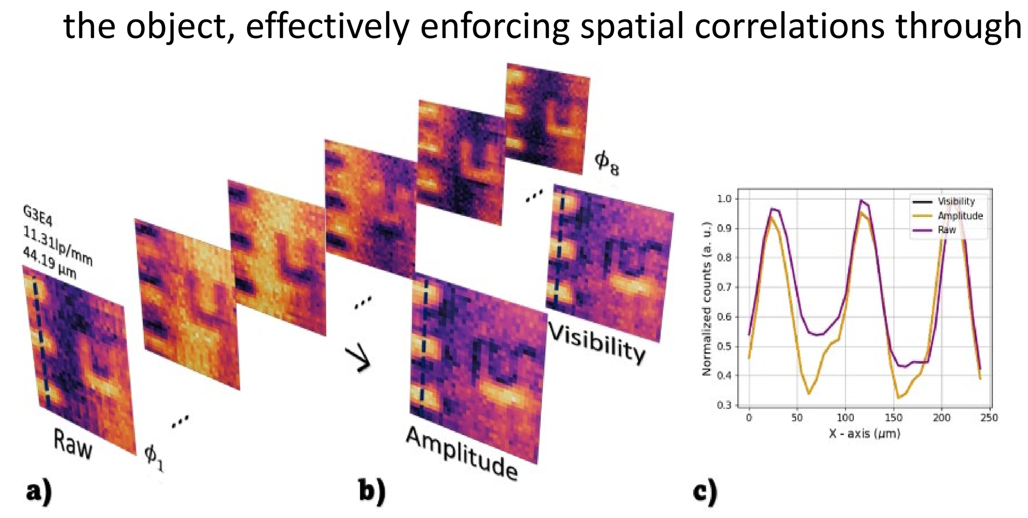


- Spontaneous parametric down-conversion (SPDC) - Generation of nonclassical light



Detection & Image formation

- The key to eliminating dependency on spatial correlations → point-wise detection scheme, where a single-pixel detector records an intensity value for each raster-scanned point of the object, effectively enforcing spatial correlations through technical means.



Amplitude:

$$A(x,y) = \frac{I_{max}(x,y) - I_{min}(x,y)}{2}$$

Visibility:

$$V(x,y) = \frac{I_{max}(x,y) - I_{min}(x,y)}{I_{max}(x,y) + I_{min}(x,y)}$$

Comparison between the raw, amplitude and visibility images. (a) Multiple images of element G3E4 acquired by controlling the interferometric phase to calculate the amplitude and visibility images shown in (b). (c) The transverse plot profile shows a minor improvement in front of the raw image, albeit at the cost of multiple frames and an extended acquisition time.

Imaging capabilities

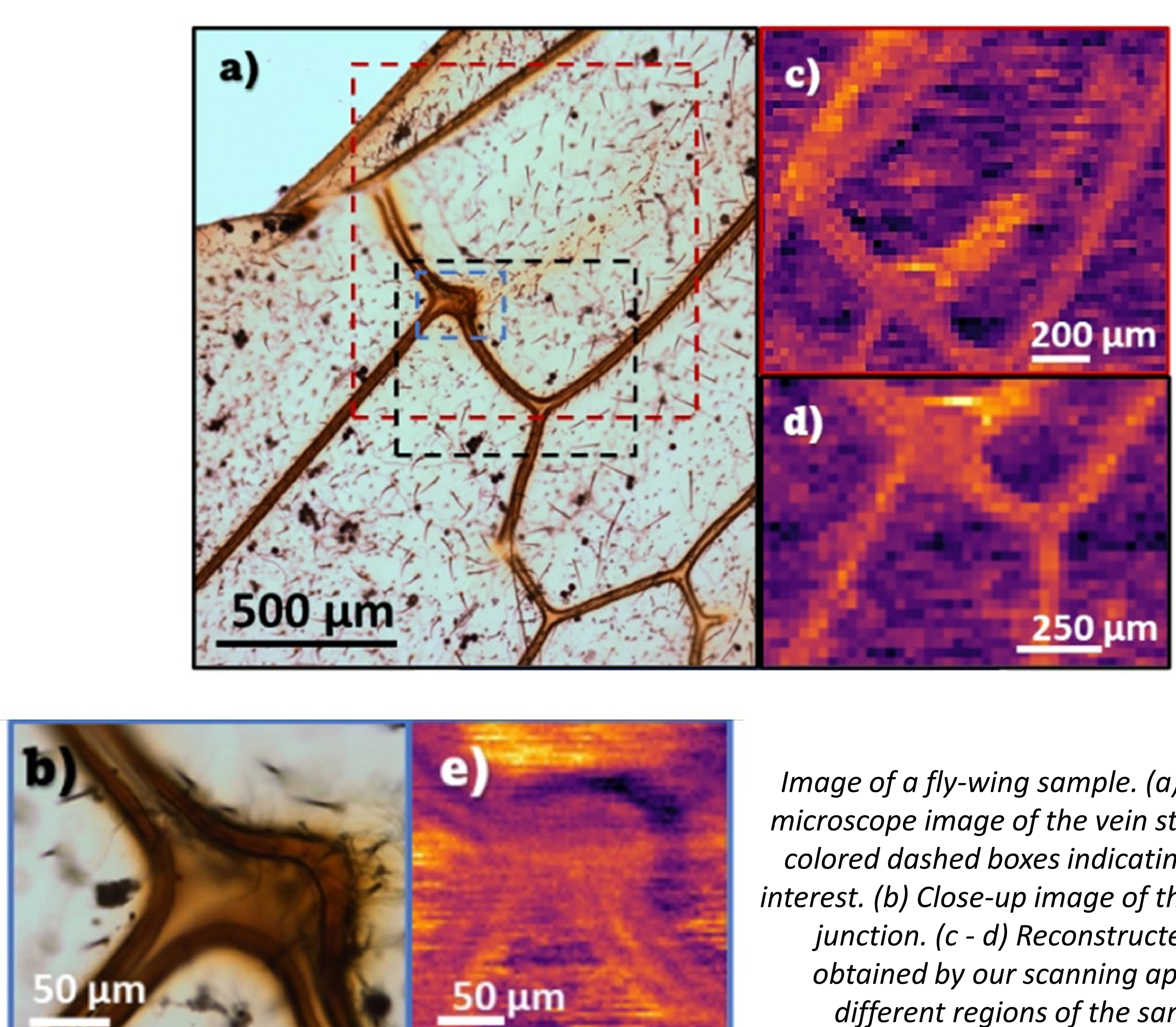
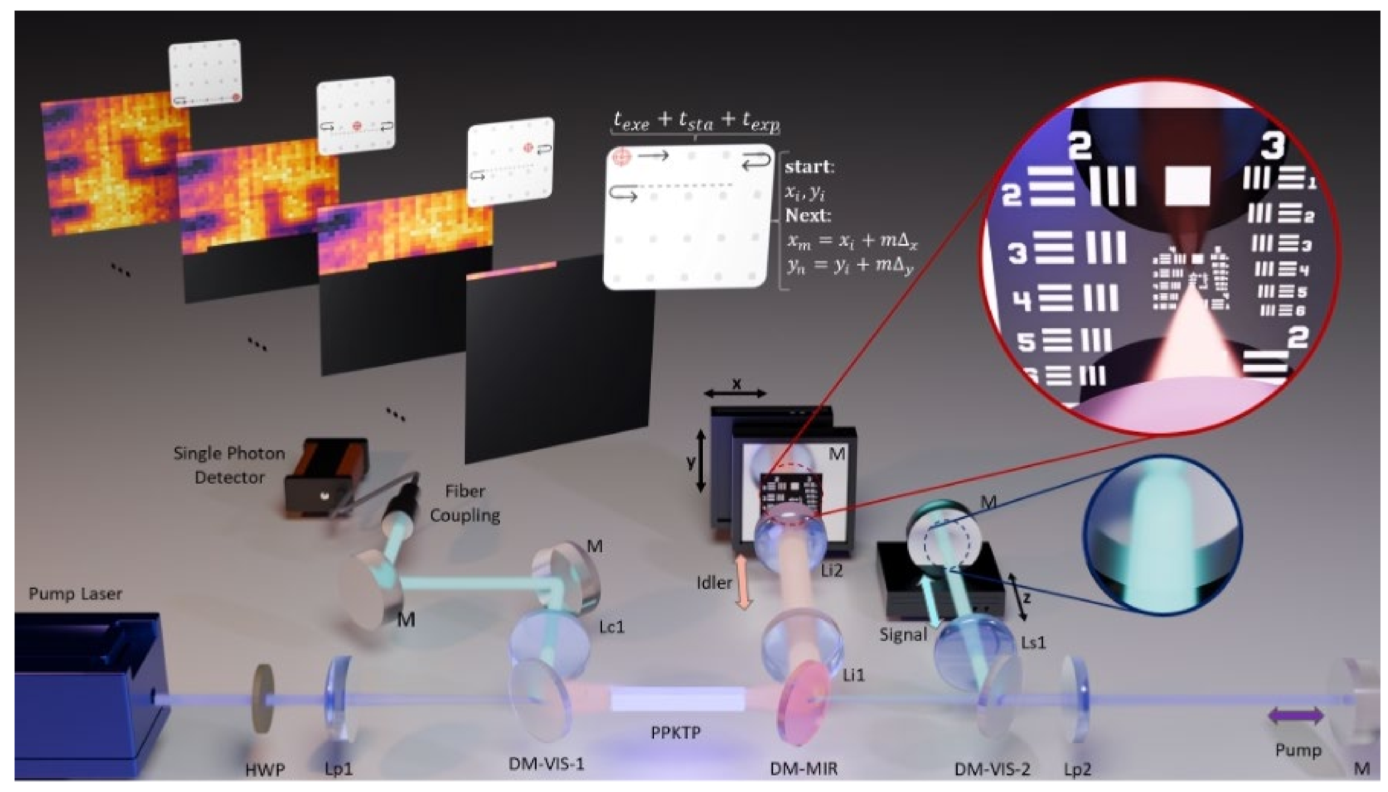


Image of a fly-wing sample. (a) White-light microscope image of the vein structure, with colored dashed boxes indicating regions of interest. (b) Close-up image of the central vein junction. (c - d) Reconstructed images obtained by our scanning approach at different regions of the sample. (e) Reconstructed image of the region indicated in (b).

Experimental set-up

Can we eliminate the influence of spatial correlations on the imaging performance of optical systems based on QIUL?

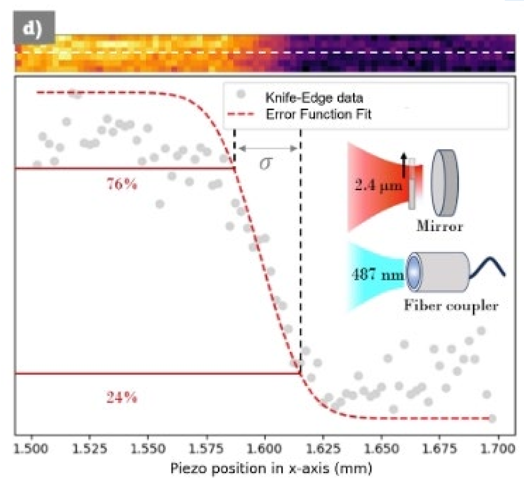


SPDC source:

- 30 mm long ppKTP, type 0
- Pump @405nm, $w_p = 75$ µm
- Signal @ 487 nm
- Idler @ 2,4 µm

Experimental set-up for MIR scanning microscopy via QIUL [3]. Double-pass folded nonlinear Michelson interferometer generates signal and idler photons, depicted in cyan and red, respectively, via SPDC. The image reconstruction process shown at the top left is conducted exclusively by the single-pixel detector.

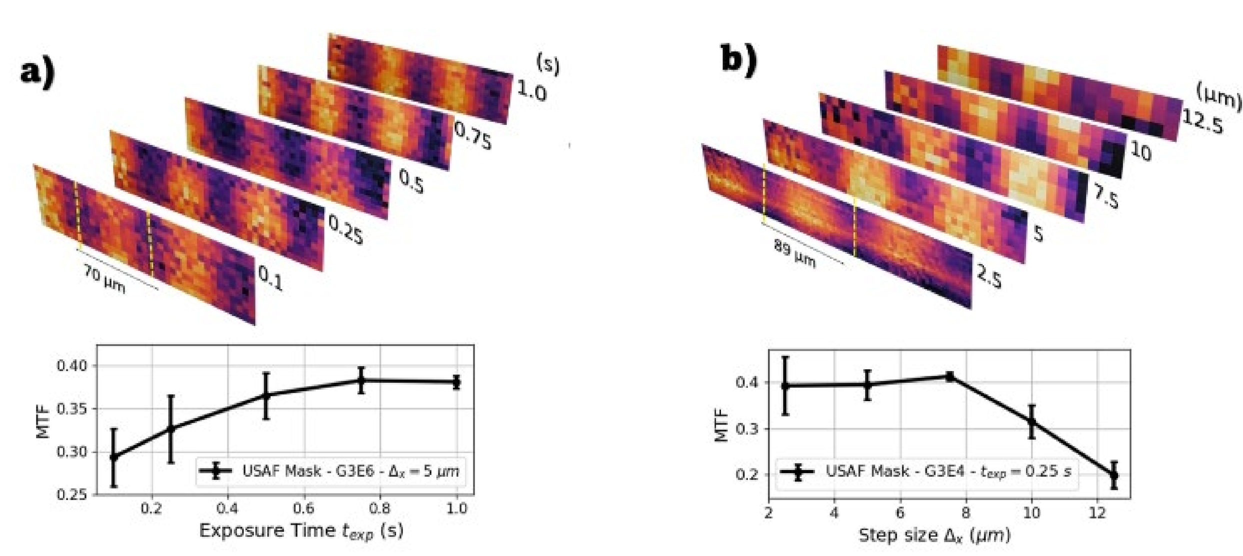
System characterization



The Knife-edge measurement of our scanning approach.

$\sigma_{scan} = 16.70 \pm 3.0\ \mu m$

- The spatial resolution of the optical system is characterized by different parameters of our imaging system. Its modulation transfer function (MTF), $MTF = \frac{\pi}{4} * CTF$, is determined, where CTF denotes the contrast transfer function given by $CTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$.



Spatial resolution characterization of the optical system through the MTF. (a) MTF as a function of the exposure time and (b) step size.

Conclusion

- Our scheme circumvents the use of spatial correlations by implementing a point-wise illumination and detection technique, resulting in an intrinsically correlated output.
- An intensity count does not rely on either position or momentum correlations for image reconstruction, but solely on the phenomenon of induced coherence without induced emission.
- Obtained spatial resolution - **16.7 ± 3.0 µm**.
- Parameters to be optimized to enhance the overall performance of our quantum imaging scheme – coated lenses with high NA, shorter chrystal, stronger pump.

REFERENCES:
[1] G. B. Lemos, V. Borish , G. D. Cole, S. Ramelow, R. Lapkiewicz, and A. Zeilinger, Nature 512, 409 (2014).
[2] X. Y.Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. 67, 318 (1991).
[3] Josué R. León Torres, et al., to be published.

Acknowledgment: This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2051 – Project-ID 390713860. In addition, this work was supported by the Horizon WIDERA 2021-ACCESS-03-01 grant 101079355 **"BioQantSense"**, from the European Union's Horizon 2020 Research and Innovation Action under Grant Agreement No. 101113901 (Qu-Test, HORIZON-CL4-2022-QUANTUM-05-SGA) and by a grant funded by the Federal Ministry of Education and Research (QUANTIFISENS - 03RU1U071M, QUANCER - 13N16441).

Email:marijac@ipb.ac.rs