Characterization of the Tunable Mid Infrared Photon Pair Sournce realized in the nonlinear $AgGaS_2$ medium

Laser microscopy – quantum and classical

Workshop within the BioQantSense project

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August 28th 2025

Funded by the European Union

HORIZON-WIDERA-2021-ACCESS-03-01 – Twinning
Grant agreement Nº 101079355

Outline

- Motivation
  - Introduction to Quantum Imaging with Undetected Photons
  - Importance of the Mid Infrared spectral range for imaging
- Experimental results
  - Realization of the Mid Infrared photon pair source in the silver-gallium-sulfide (AGS) medium
- Future work
  - Building an interferometer utilizing the AGS photon pair source for bioimaging in the mid infrared spectral region

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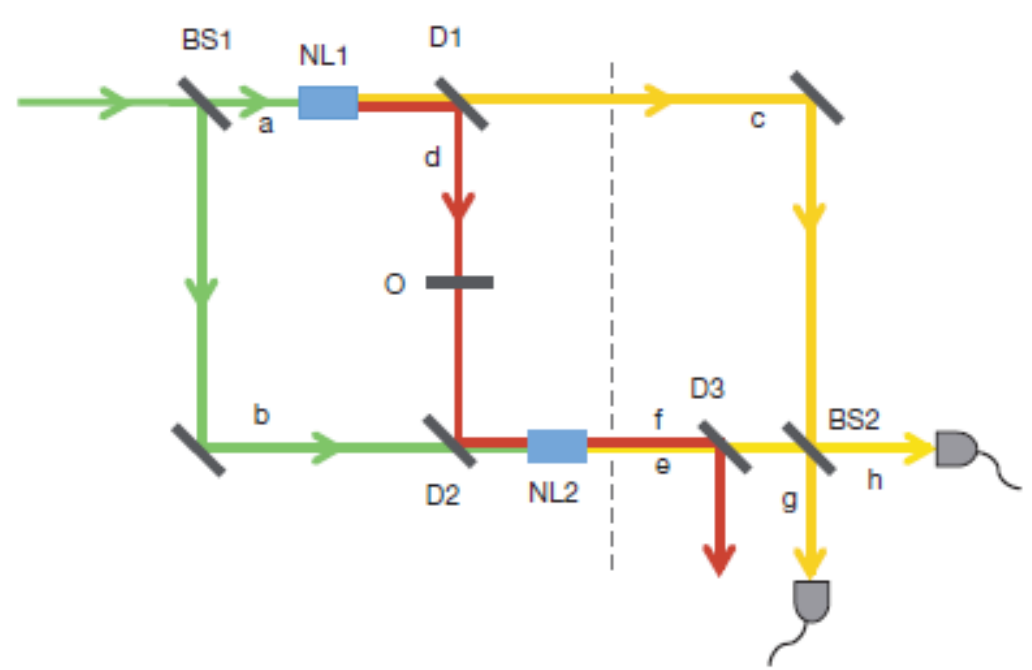
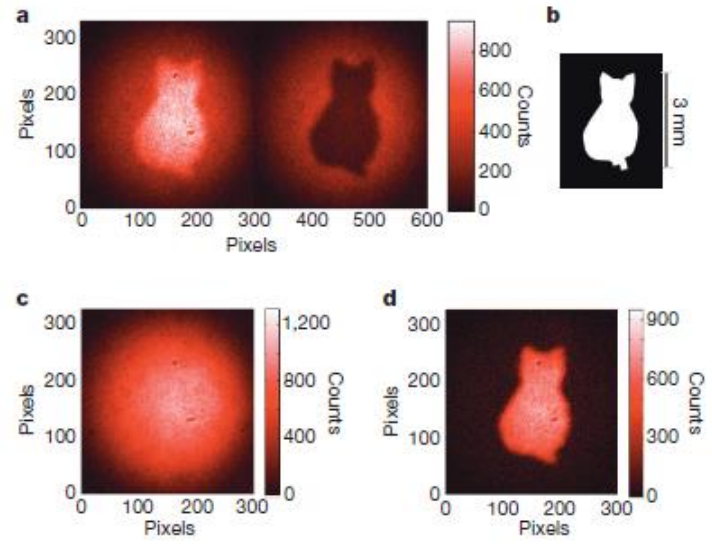
Motivation

- Quantum Imaging with Undetected Photons (QIUP)
- Spontaneous parametric down-conversion (SPDC)
  - Pump photon gets converted into signal-idler photon pair
  - Induced coherence without induced emission
- Imaging only signal photons which never interacted with the object directly





G. B. Lemos, V. Borish, G. D. Cole, S. Ramelow, R. Lapkiewicz, and A. Zeilinger, "Quantum imaging with undetected photons.," *Nature*, vol. 512, no. 7515, pp. 409–412, Aug. 2014, doi: 10.1038/nature13586

Motivation

- Importance of the Mid Infrared spectral range for imaging
  - Absorption bands for many molecules, functional groups
  - Fingerprint region
- Suitable medium for photon generation in the fingerprint region?
  - Potassium-titanyl-phosphate (KTP) and Lithium-Niobate (LN) have low transparency above 5 µm

G. Bellisola and C. Sorio, "Infrared spectroscopy and microscopy in cancer research and diagnosis.," *Am. J. Cancer Res.*, vol. 2, no. 1, pp. 1–21, 2012.

Wavenumber (cm^{-1})	Functional group	Vibrational mode	Commonly assigned biochemical component
3500 - 2500	X-H stretching vibrations (where X is C, O, or N)		
~3300	N–H	ν(N–H)	Amide A: peptide, protein
~3100	N–H	ν(N–H)	Amide B: peptide, protein
2957	C–CH_3	$\nu_{as}(CH_3)$	lipids
2920	–$(CH_2)_n$–	$\nu_{as}(CH_2)$	
2872	C–CH_3	$\nu_s(CH_3)$	
2851	–$(CH_2)_n$–	$\nu_s(CH_2)$	
2000 - 1500	fundamental stretching vibrations of double bonds (e.g., C=O, C=C, C=N)		
~1740	–CH_2–COOR	ν(C=O)	Phospholipid esters
~1655	O=C–N–H	80% ν(CO), 20% ν(CN)	Amide I peptide, protein
~1645	H–O–H	γ(HOH)	Water
~1545	O=C–N–H	60% γ(N–H), 30% ν(C–N), 10% ν(C–C)	Amide II peptide, protein
~1500 - 600	the "fingerprinting region": many overlapped vibrations		
~1450	–$(CH_3)_n$– –$(CH_2)_n$	$\delta_{as}(CH_3)$ $\delta_{as}(CH_3)$	Lipid, protein
~1395	–$(CH_3)_n$– –$(CH_2)_n$ $^-$O–C=O	$\delta_s(CH_3)$ $\delta_s(CH_3)$ ν(C=O)	Lipid, protein
~1380	C–CH_3	$\gamma_s(CH_3)$	Phospholipid, fatty acid, triglyceride
1400 - 1200	O=C–N–H, CH_3	γ(N–H), ν(C–N), γ(C=O), ν(C–C) and ν(CH_3)	Amide III peptide, protein, collagen
~1245 - 1230	RO–PO_2^-–OR	$\nu_{as}(PO_2^-)$	DNA, RNA, phospholipid, phosphorylated protein
~1170	R–COO–R'	ν_{as}(C–O)	Ester
~1160 and ~1120		ν(C–O)	RNA ribose
~1150	C–O, C–O–H	ν(CO), γ(COH)	carbohydrates
~1095, ~1084, ~1070	RO–PO_2^-–OR	$\nu_s(PO_2^-)$	DNA, RNA, phospholipid, phosphorylated protein
~1078	C–C	ν(CC)	glycogen
~1060, 1050, 1015	C–O	ν(CO)	DNA and RNA ribose
~1050	C–O–P	ν(COP)	Phosphate ester
~1028	C–O–H	def(CHO)	glycogen
~965	PO_3^{2-}	ν(PO_3^{2-})	DNA and RNA ribose
~950	P–O	ν(PO_3^{2-})	Phosphorylated protein
~920	C–O–P	ν(COP)	Phosphorylated protein

ν, stretching; δ, bending; γ, wagging, twisting, and rocking; def, deformation, as, antisymmetric; s, symmetric.

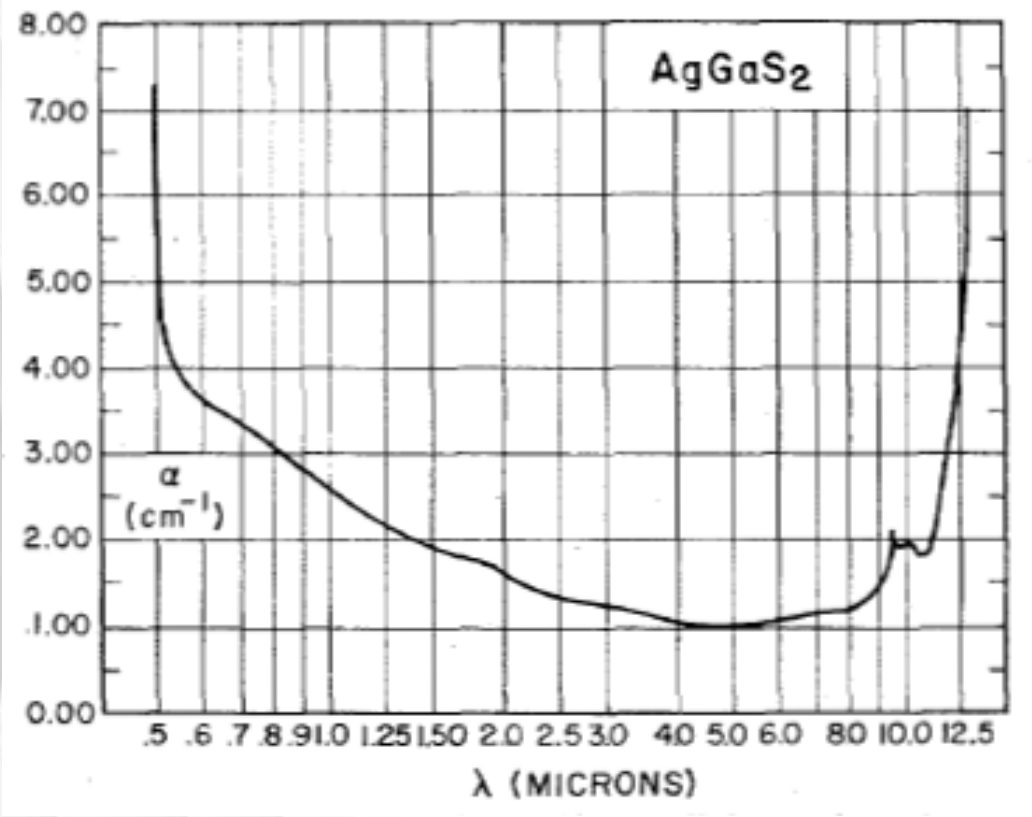
Silver-Gallium-Sulfide (AGS)

- Low absorption coefficient from 5 µm to 12.5 µm
- SPDC in type I-configuration

$$p^e \rightarrow s^o + i^o$$

- Nonlinear coefficient for type I conversion

$$d_{eoo} = -d_{36} \sin\theta \sin(2\varphi)$$



G. Boyd, H. Kasper, and J. McFee, "Linear and nonlinear optical properties of AgGaS2, CuGaS2, and CuInS2, and theory of the wedge technique for the measurement of nonlinear coefficients," *IEEE J. Quantum Electron.*, vol. 7, no. 12, pp. 563–573, 1971, doi: 10.1109/JQE.1971.1076588.

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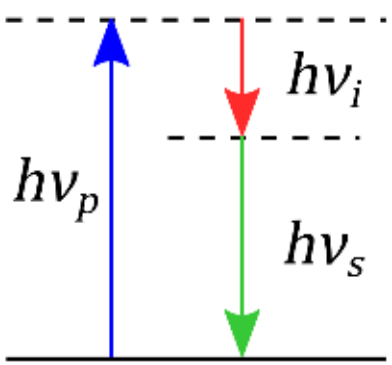
Silver-Gallium-Sulfide (AGS)

- Phase matching condition

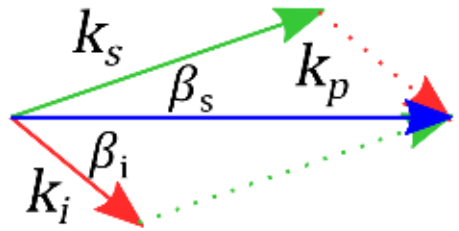
$$\Delta k = \frac{2\pi n_e(\lambda_p, \theta)}{\lambda_p} - \frac{2\pi n_o(\lambda_s)}{\lambda_s}\cos(\beta_s) - \frac{2\pi n_o(\lambda_i)}{\lambda_i}\cos(\beta_i)$$

$$0 = \frac{2\pi n_o(\lambda_s)}{\lambda_s}\sin(\beta_s) - \frac{2\pi n_o(\lambda_i)}{\lambda_i}\sin(\beta_i)$$



$$h\nu_p = h\nu_s + h\nu_i$$

Energy conservation



$$k_p = k_s + k_i$$

Momentum conservation

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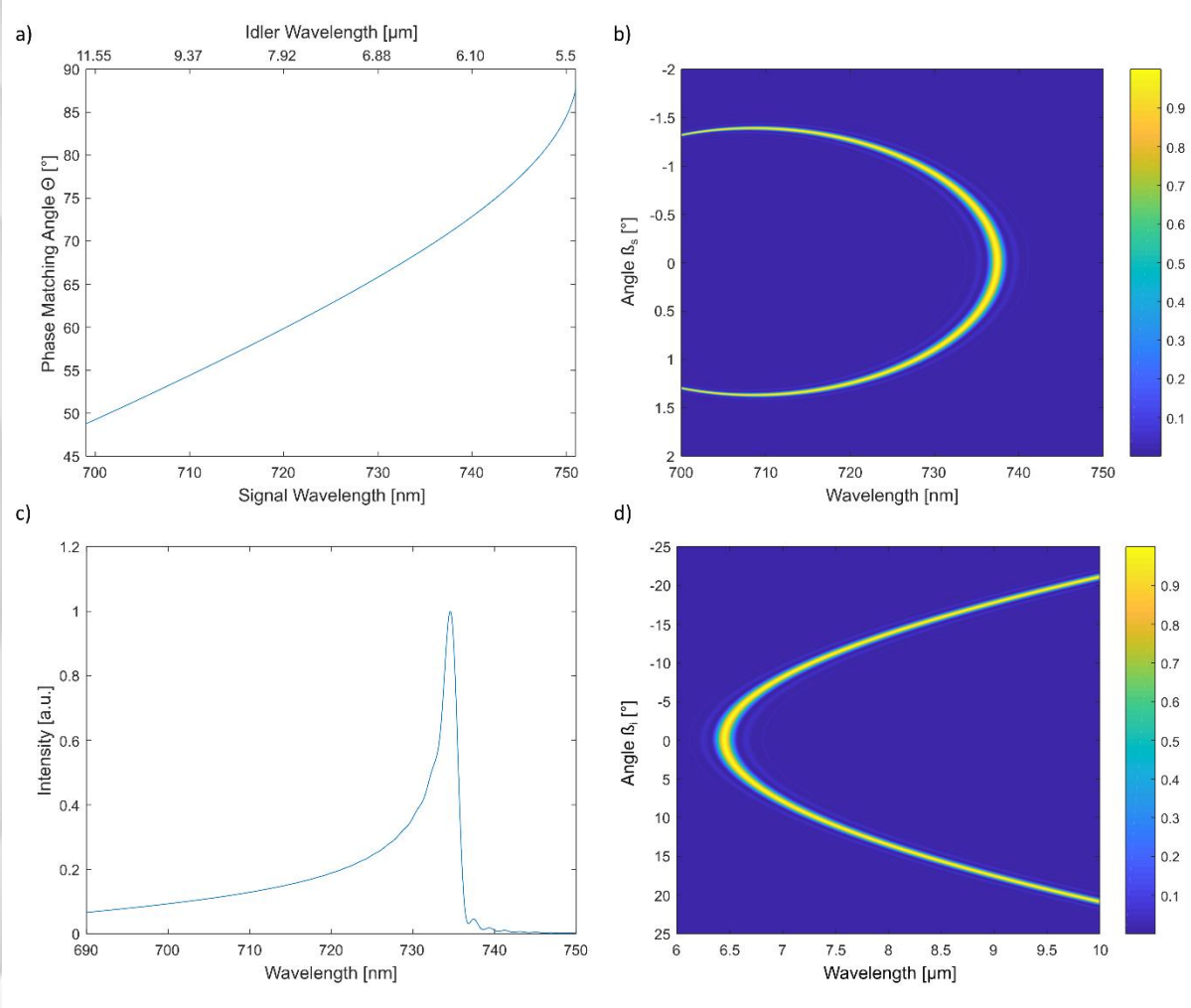
Silver-Gallium-Sulfide (AGS)

- Pump laser at 660 nm
- Phase matching condition
  - Phase matching angle
  - Frequency angular spectrum
- Nonlinear coefficient for type I conversion

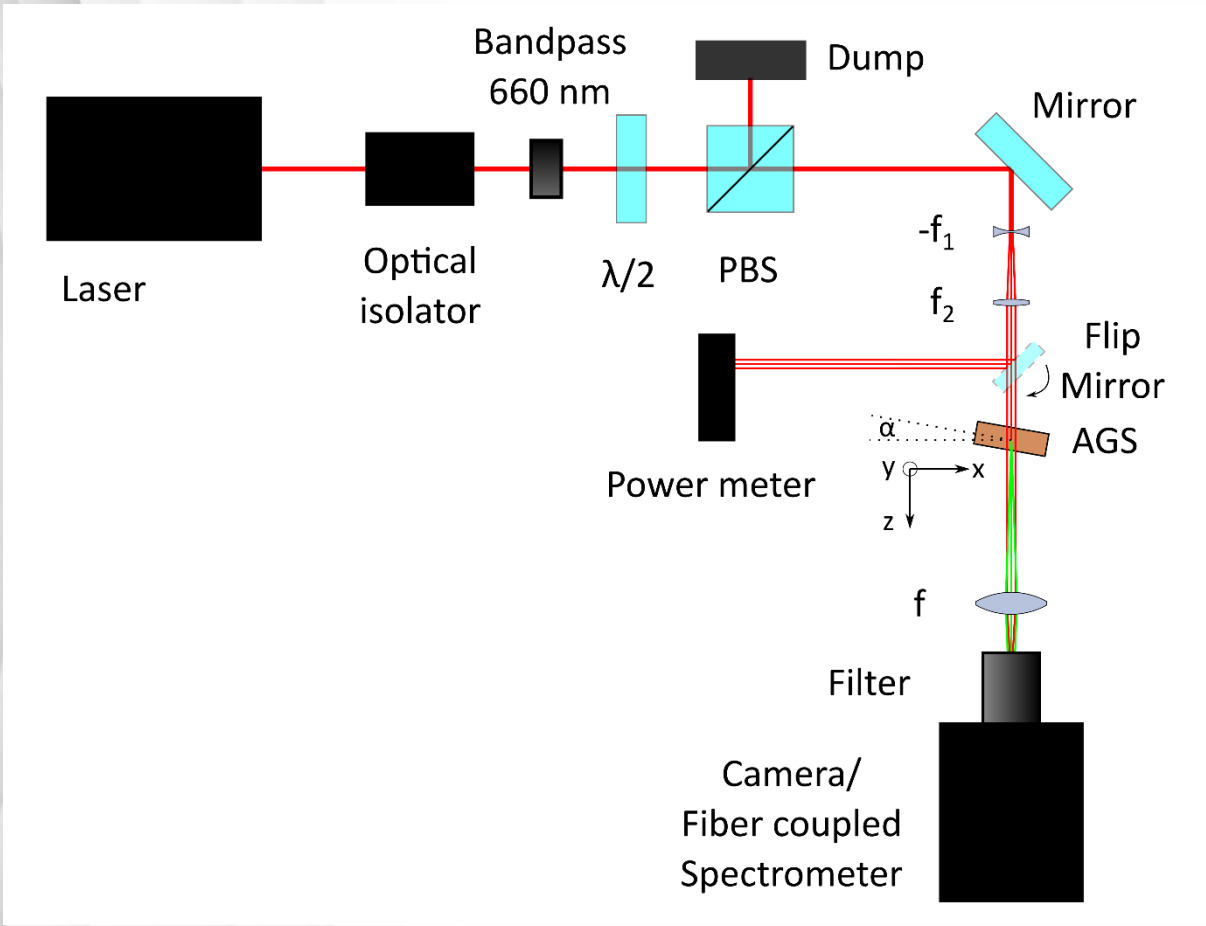
$$d_{eoo} = -d_{36} \sin\theta \sin(2\varphi)$$

- AGS (polar angle $\theta = 70°$, azimuth angle $\varphi = 45°$, length 1 mm, face dimensions 5 mm*5 mm)



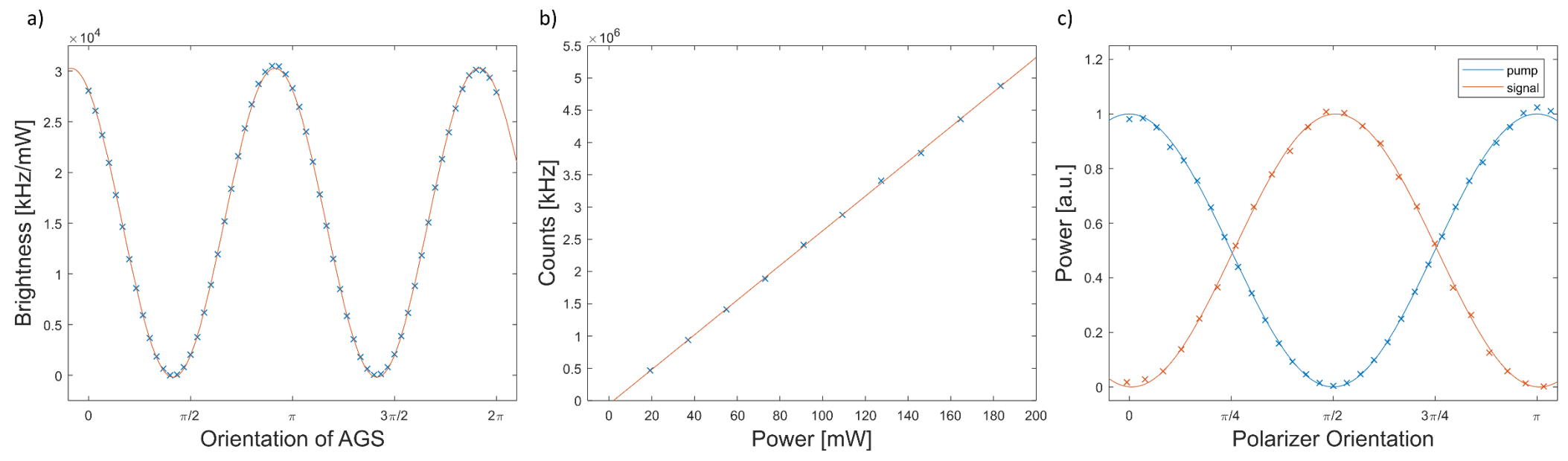
Realization of the mid infrared photon pair source in AGS

- Experimental setup
  - Pump laser - Hübner Photonics, Cobolt Flamenco (wavelength 660 nm, optical power 30 mW – 300 mW)
  - Camera - Tucsen, Dhyana 400BSI V3 / Spectrometer - Avantes, AvaSpec-ULS2048XL-EVO (exposure time 0.5 s – 1 s)
- Filters
  - Notch filter 657 nm
  - Longpass filter 685 nm
  - Bandpass filter 730 nm (FWHM 10 nm)



Realization of the mid infrared photon pair source in AGS

- Brightness, Photon count and state of polarization



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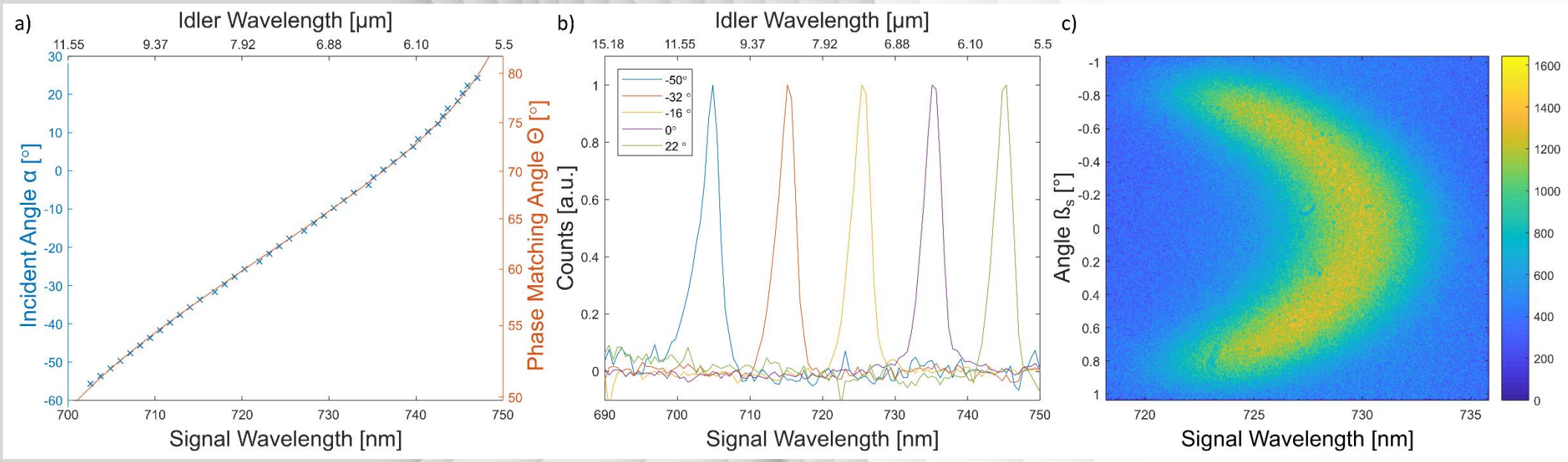
Realization of the mid infrared photon pair source in AGS

- Spectral characterization



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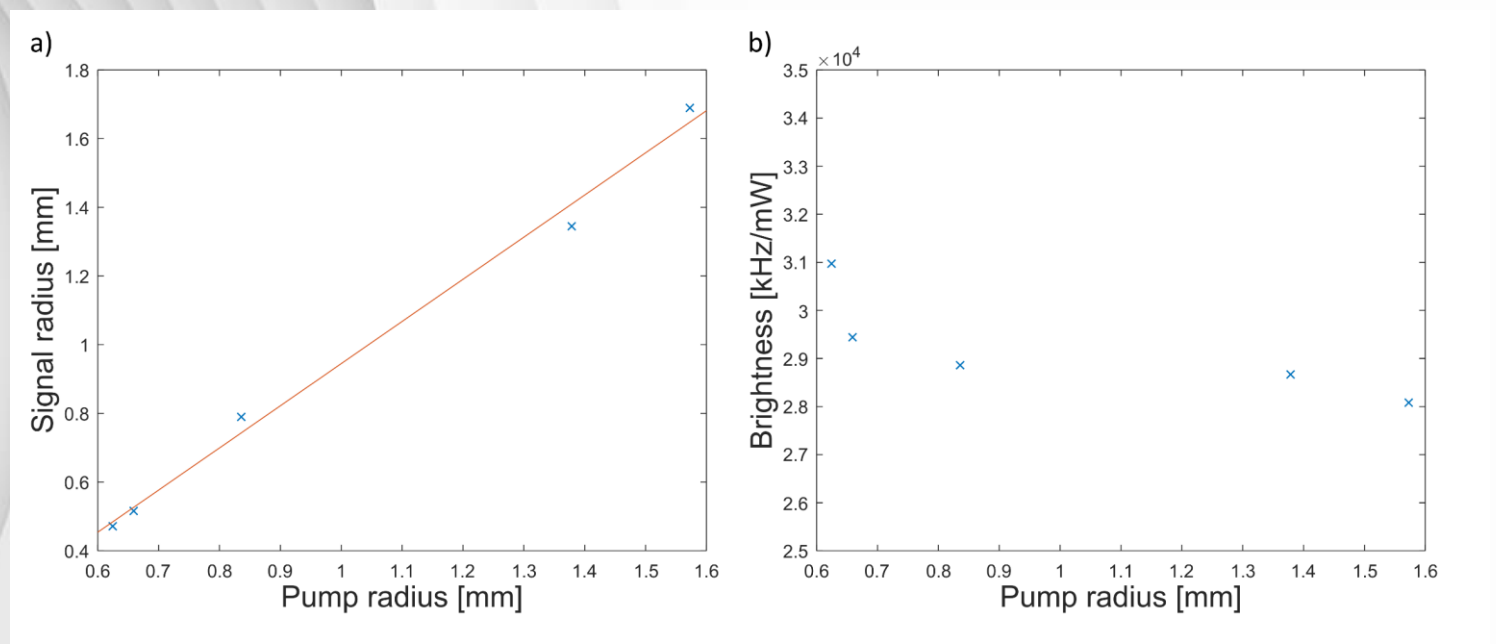
Realization of the mid infrared photon pair source in AGS

- Signal beam radius and photon count

- Brightness

$$(2.92 \pm 0.11) * 10^4 \frac{kHz}{mW}$$



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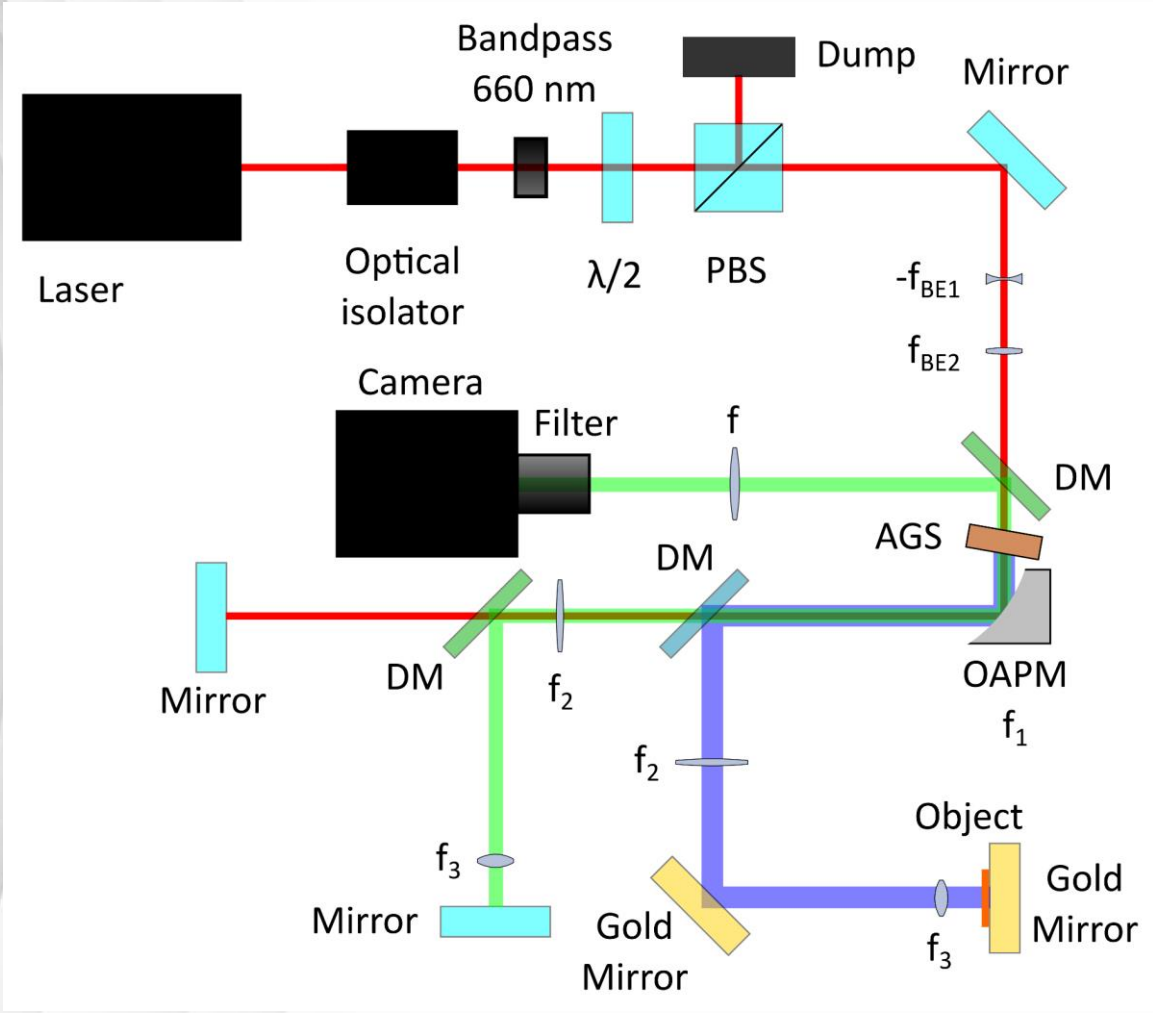
Future work

- Building the Quantum Interferometer with the AGS crystal
- Momentum correlation (far-field)
- Resolution

$$\Delta = \frac{f_3 f_1}{f_2} \frac{\lambda_i}{\sqrt{2}\pi w_p}$$

$$f_1 = 50\ mm, f_2 = 300\ mm,$$
$$f_3 = 25.4\ mm$$



Thank you for the attention

Feel free to ask any questons

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