Quantum interferometry with undetected photons in mid-infrared spectrum

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Outline

- Introduction
    - Mid-infrared spectrum
    - Spontaneous parametric down-conversion
- Tunable mid-infrared photon source in $AgGaS_2$
    - Experimental setup and results
- Quantum interferometry in mid-infrared
    - Future work in imaging
    - Application in spectroscopy

Mid-infrared spectrum

- 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 $\nu(CH_3)$	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-}	$\nu(PO_3^{2-})$	DNA and RNA ribose
~950	P–O	$\nu(PO_3^{2-})$	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.

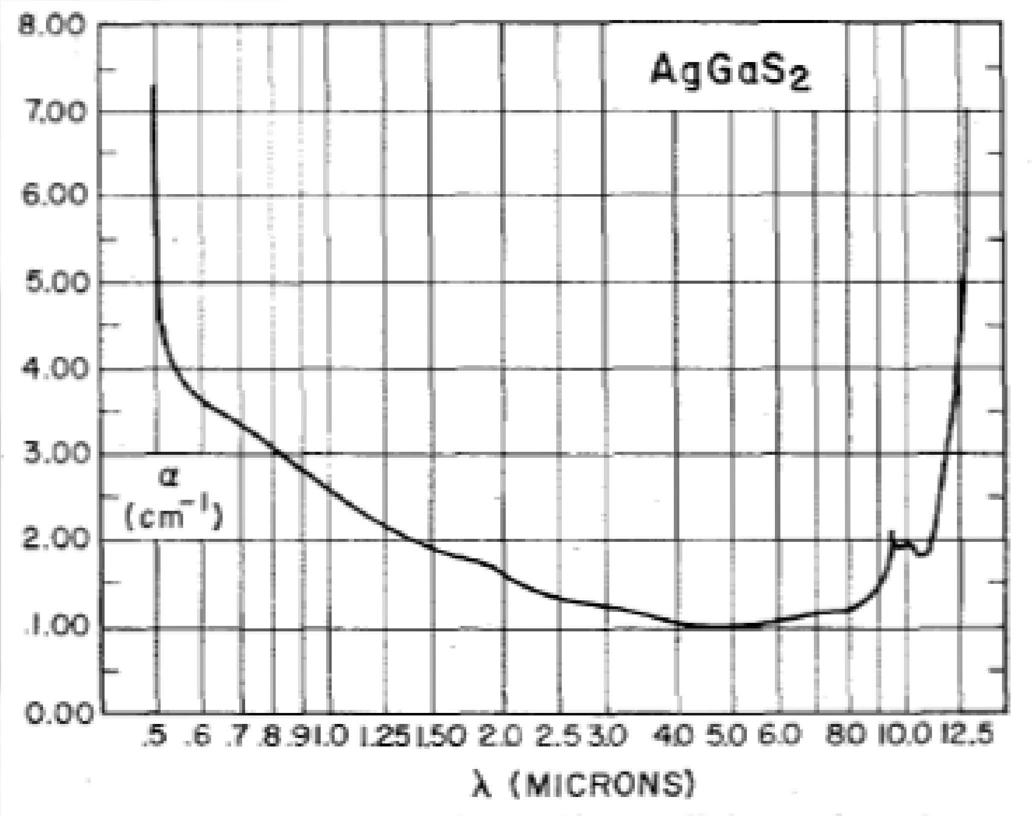
Mid-infrared spectrum

- Silver-Gallium-Sulfide (AGS)
- Low absorption coefficient from 500 nm 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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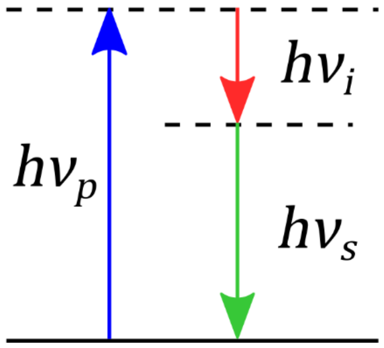
Photon pair source

- Spontaneous parametric down-conversion (SPDC) in the nonlinear medium
  - Spatial, spectral and polarization correlation
  - Phase matching condition

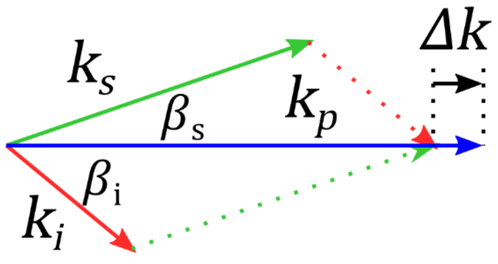
$$\Delta k = \frac{2\pi n_e(\lambda_p,\theta)}{\lambda_p} - \frac{2\pi n_o(\lambda_s)}{\lambda_s}\cos(\beta_s) - \frac{2\pi n_o(\lambda_i)}{\lambda_i}\cos(\beta_i)$$

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



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

Energy conservation

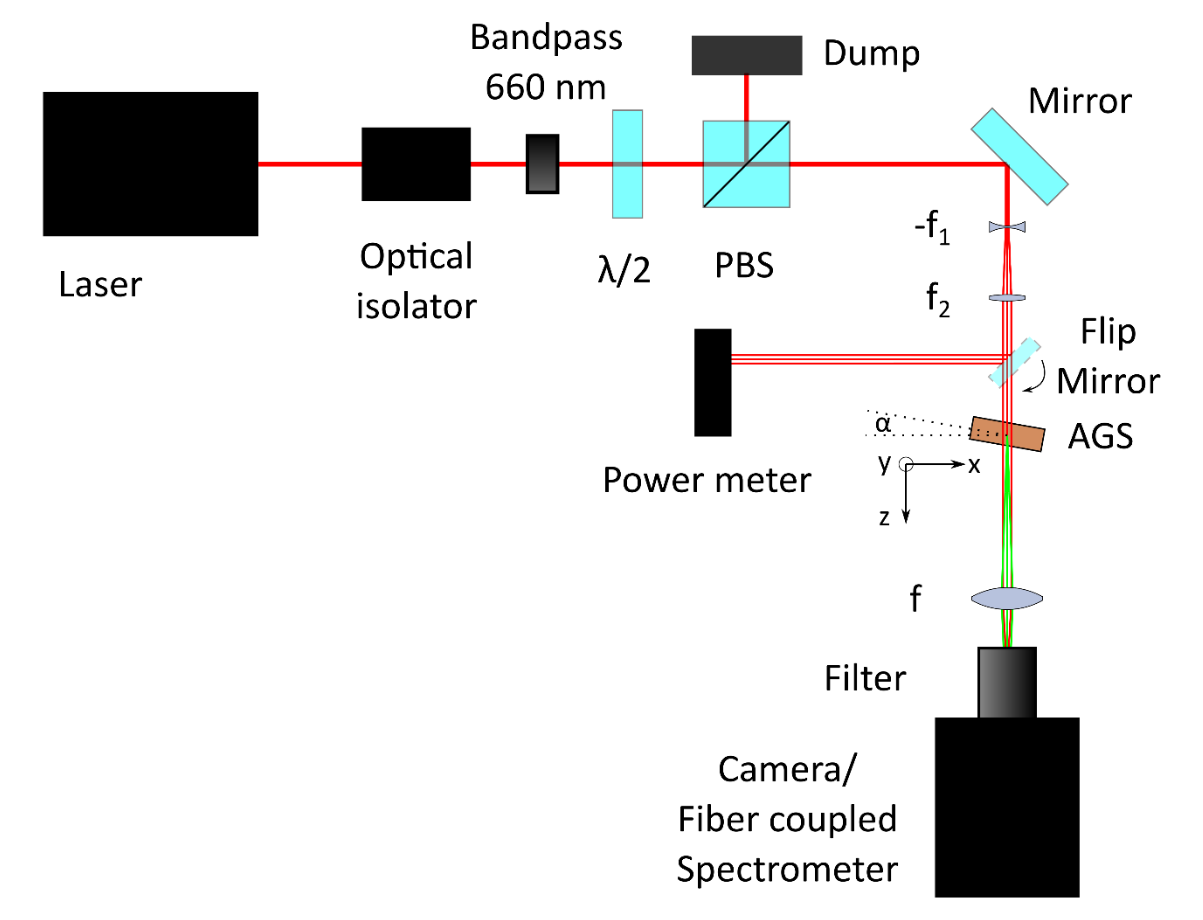


$\Delta k = k_p - k_s - k_i$

Momentum conservation

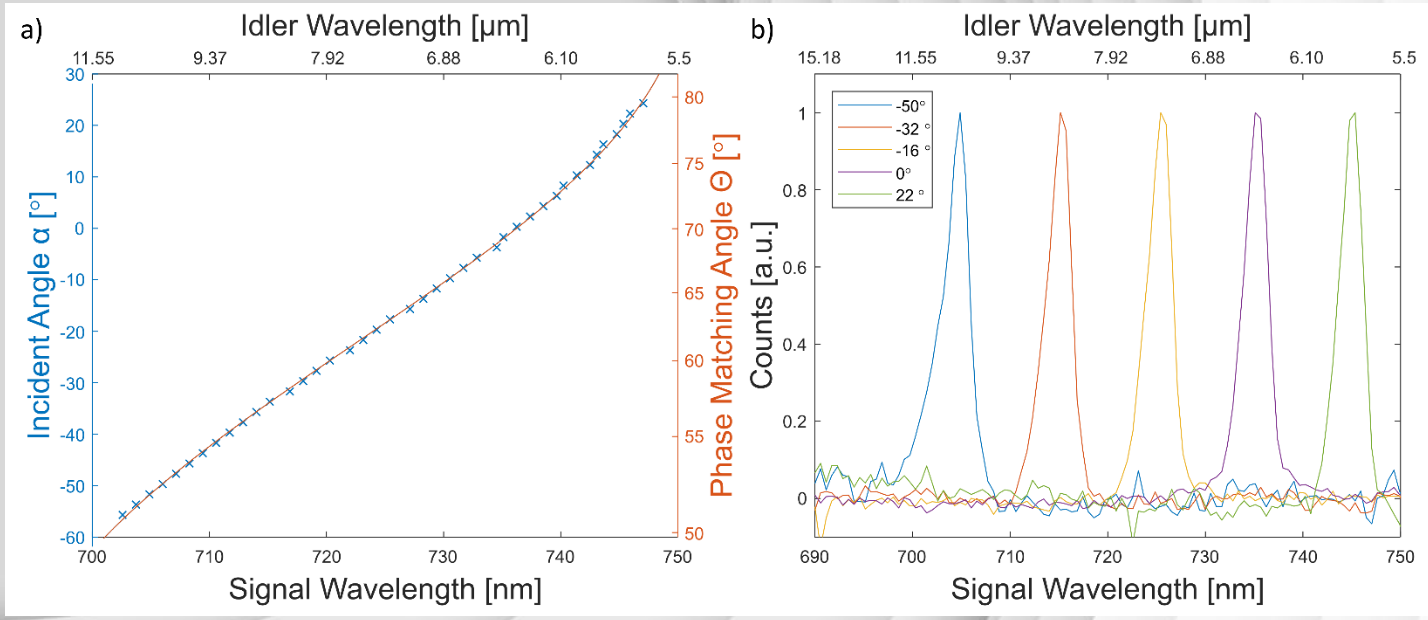
MIR photon source in AGS

- 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)



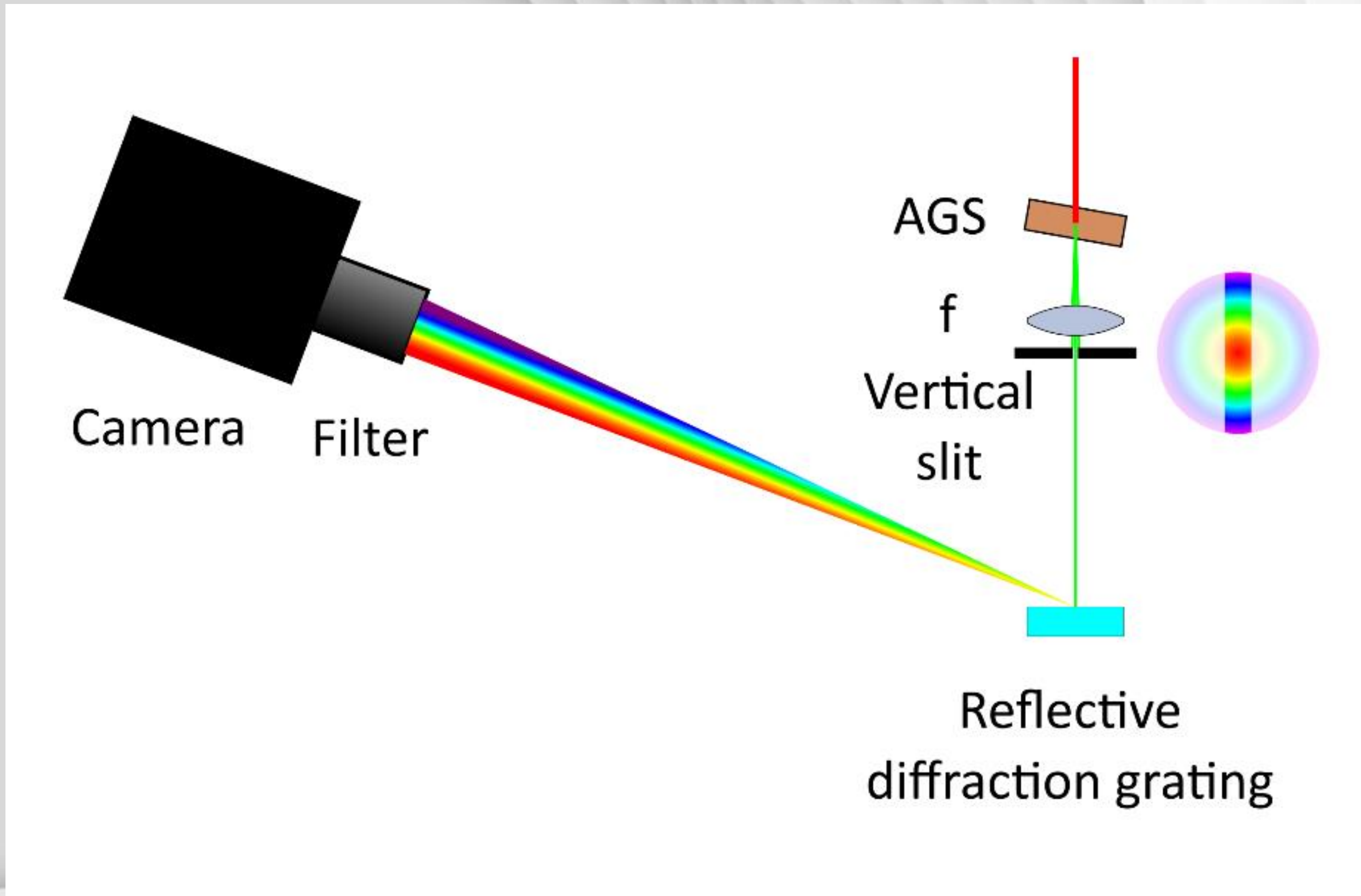
MIR photon source in AGS

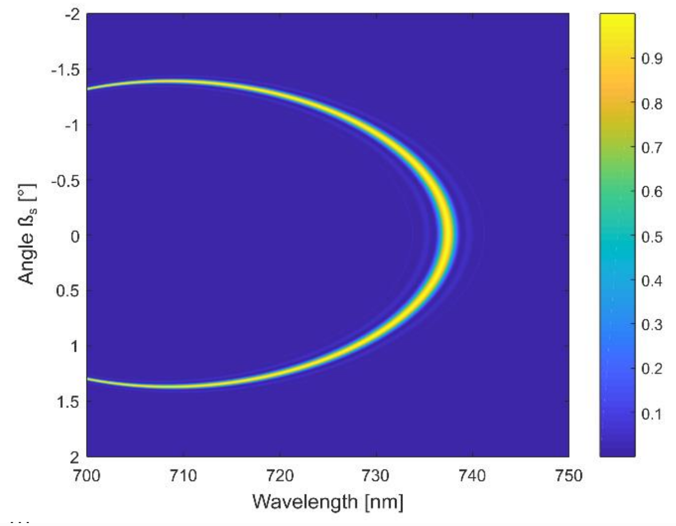
- Spectral characterization
  - Phase matching angle
    - Idler $5.66\ \mu m$ to $10.88\ \mu m$
    - Signal 747.1 nm to 702.6 nm
- Signal/idler spectrum
  - FWHM $(54.192 \pm 2.603) cm^{-1}$

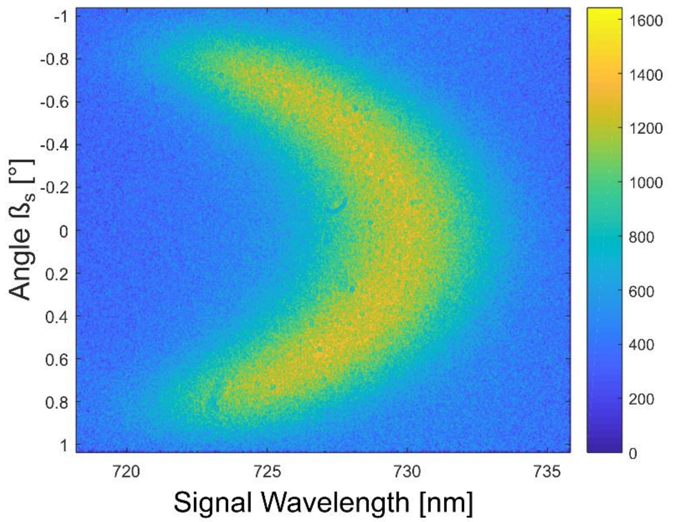


MIR photon source in AGS

- Signal's frequency-angular spectrum





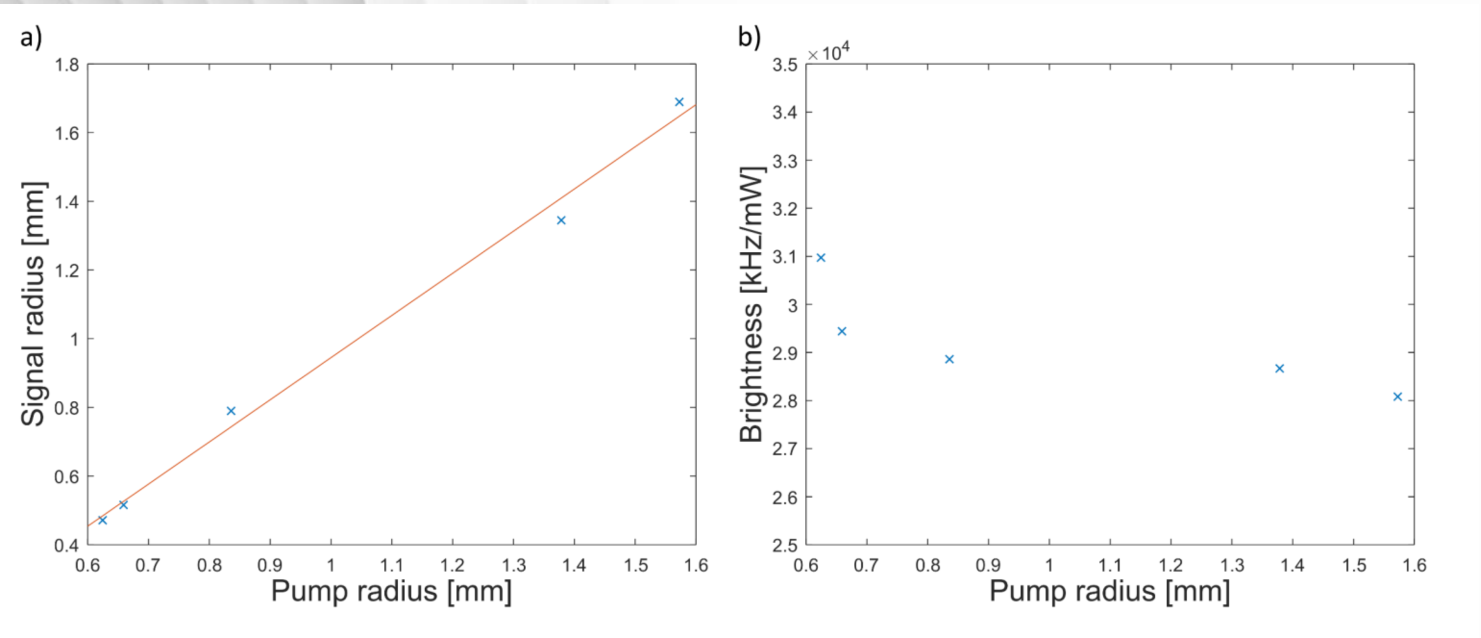


MIR photon source in AGS

- Signal beam radius and photon count

- Brightness

$$(29.2 \pm 1.1)\frac{MHz}{mW}$$

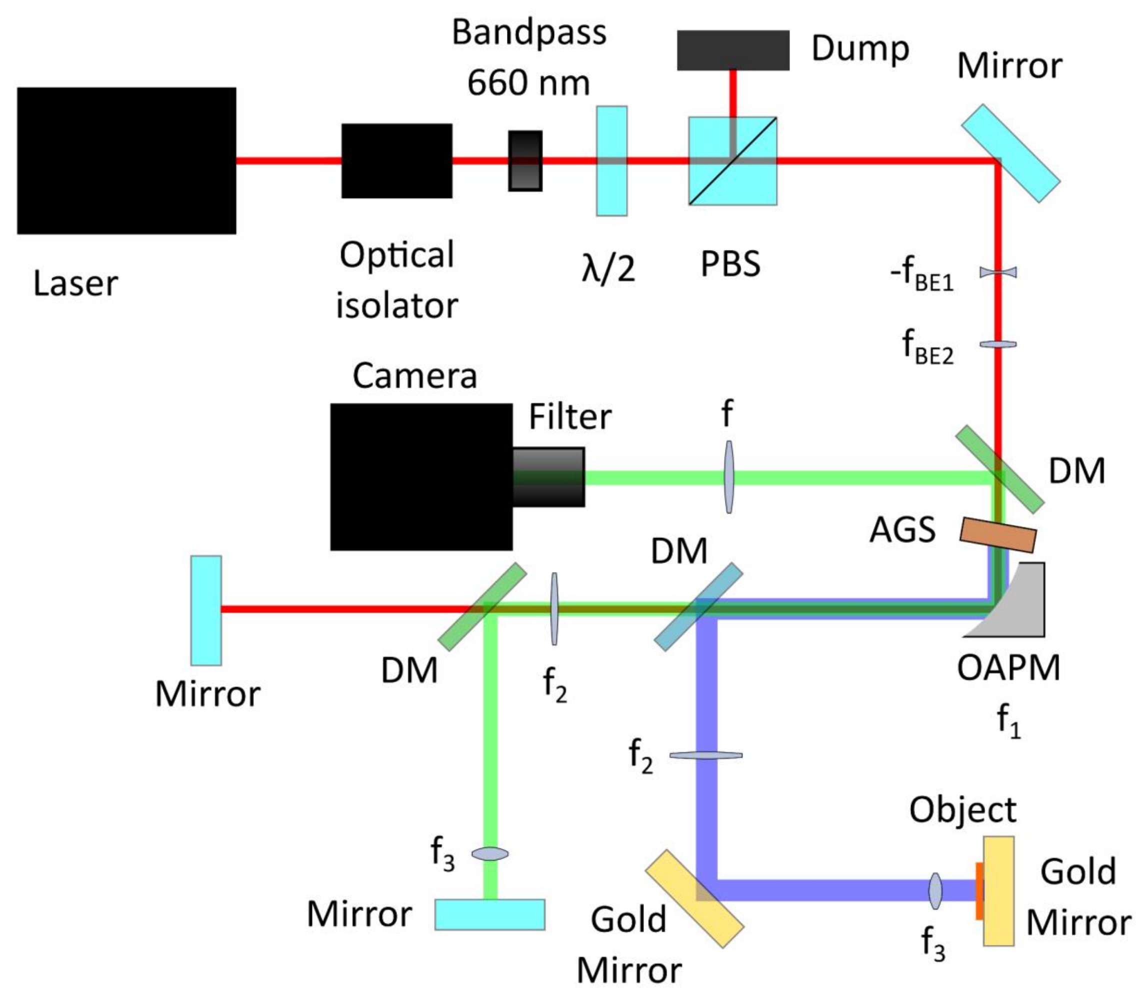


Quantum interferometry in mid-infrared

- Quantum imaging with the AGS
- Induced coherence without induced emission
- Momentum correlation (far-field)
- Resolution

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

$$f_1 = 50\ mm, f_2 = 200\ mm,$$
$$f_3 = 25.4\ mm$$



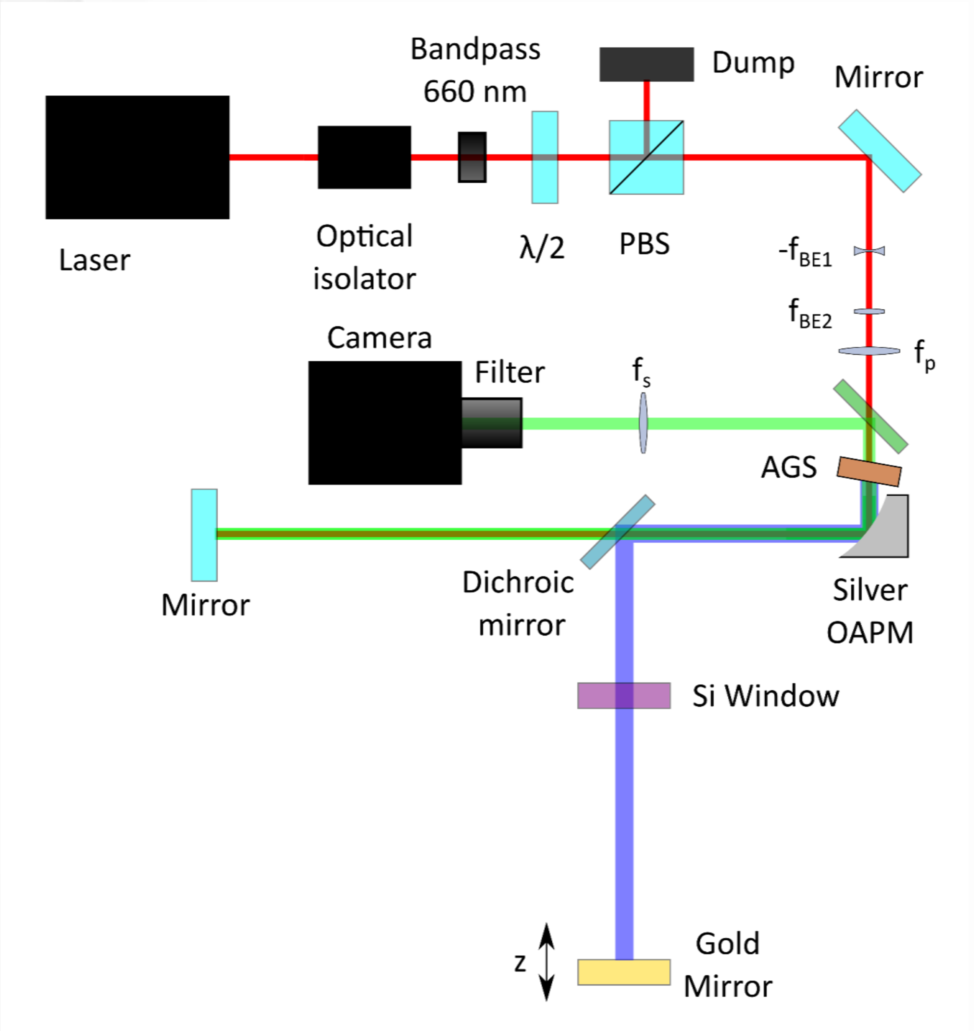
Quantum interferometry in mid-infrared

- Quantum Fourier Transform Infrared Spectroscopy (qFTIR)
  - Moving gold mirror ($\Delta z = 500$ nm) induces phase shift for idler photons
  - Total scanning length (W = 800 μm)
  - Spectral resolution

$$\Delta k = \frac{1}{W} = 12.5\ cm^{-1}$$

  - Coherence length

$$L_c = \frac{1}{FWHM\ [cm^{-1}]} = 184.09\ \mu m$$

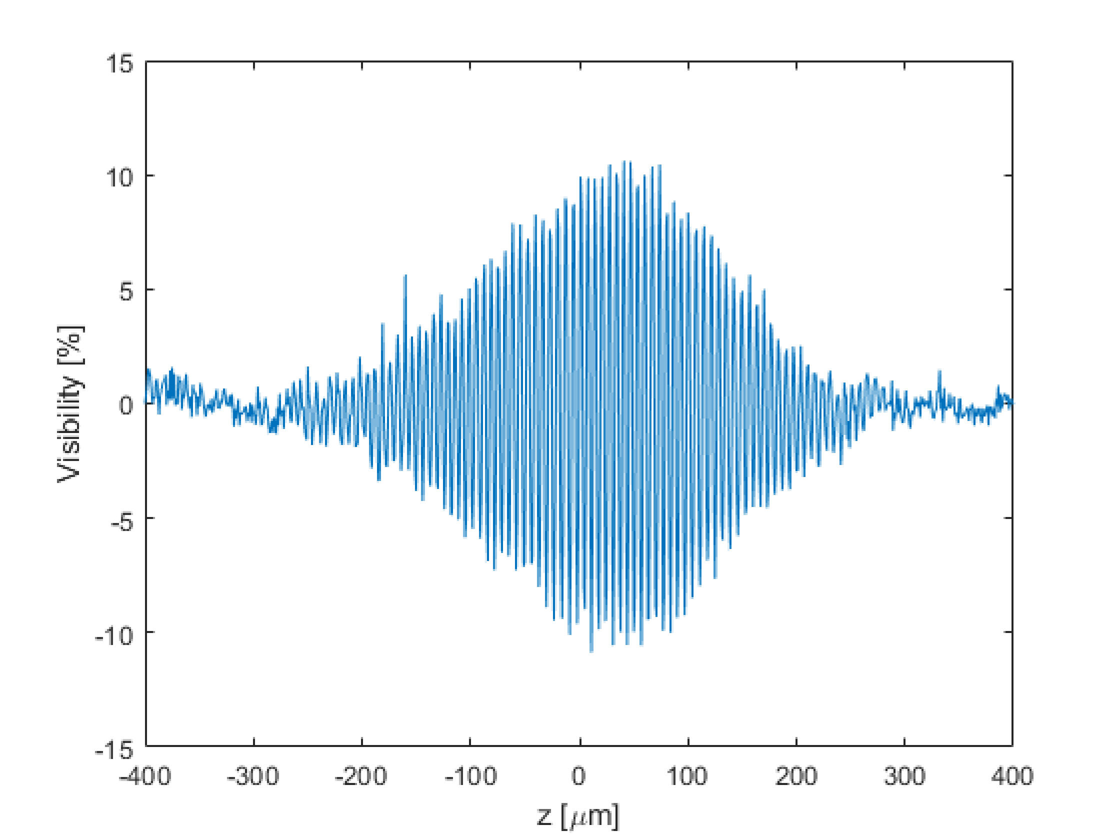


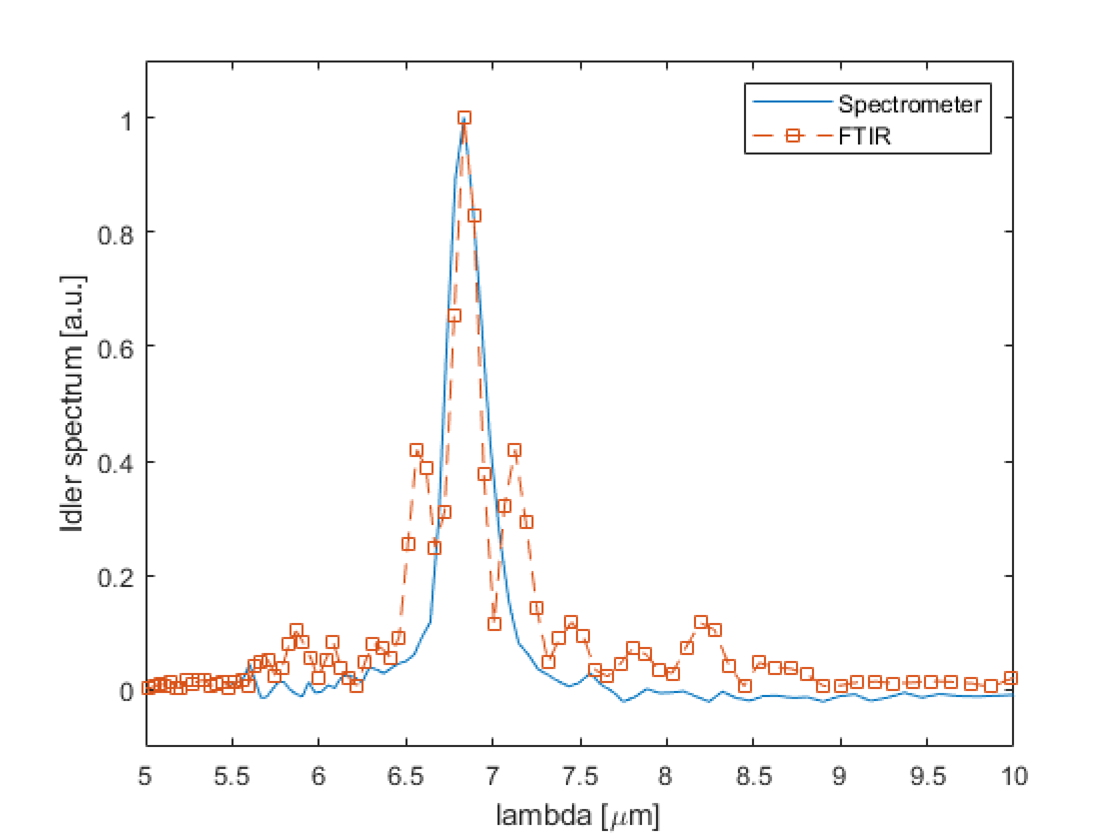
Quantum interferometry in mid-infrared

- Interferogram obtained from signal photons

FT

- FTIR spectrum of idler photons





Conclusion

- Tunable MIR SPDC photon source in AGS was demonstrated
  - Idler $5.66\ \mu m$ to $10.88\ \mu m$
- Quantum interferometer in MIR was realized
  - Application in qFTIR spectroscopy
- Future work
  - Measuring MIR spectra for different samples
  - Upgrading the interferometer for quantum imaging in MIR

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Thank you for your attention

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