Controlling spatial modes in waveguided spontaneous parametric down conversion

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Plan:

- PP-KTP waveguide characteristics,
- Spatial mode dependent phase matching,
- Single spatial mode down conversion,
- Summary & outlook.

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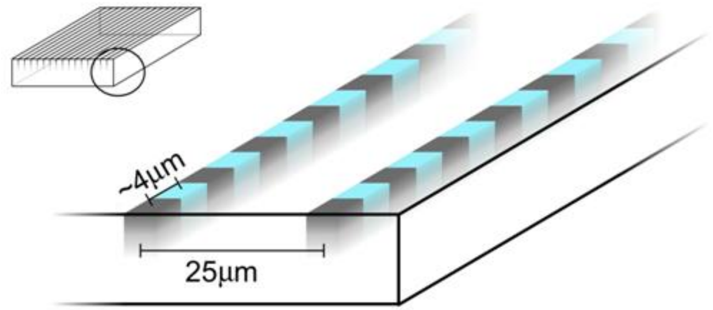
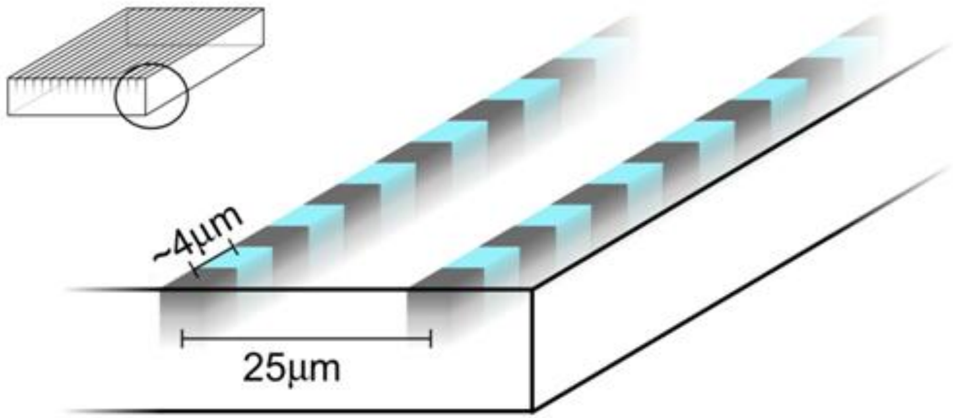
Three wave mixing (SFG, SPDC) in periodically poled $KTiOPO_4$ waveguides



Motivation:

- high efficiency
    - quasi phase matching
    - tight light confinement
    - collinear
- spatial characteristics defined by the waveguide geometry;
- integrated devices
- easy experimental setup.

PP-KTP waveguides

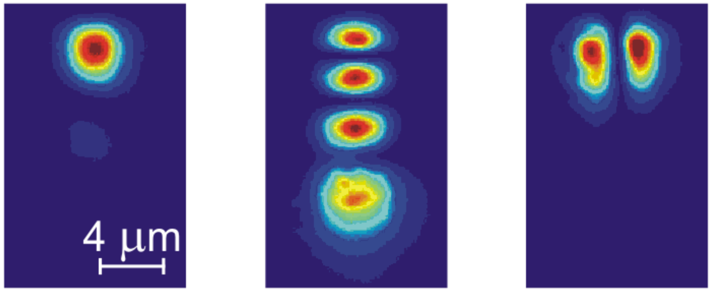


Waveguide characteristics

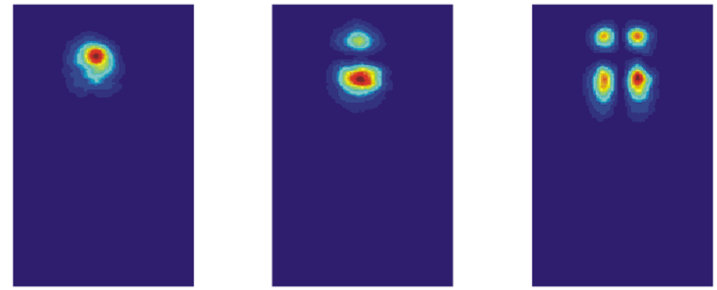
- waveguide chip – KTP crystal with >50 waveguides under the surface,
- width 2, 3 or 4 µm, depth ~ 6 µm,
- 4 mm and 1 mm sample lengths,
- type II quasi phase matched @ 800 nm.
- produced by ion exchange (AdvR Inc.) → diffusion leads to exponential refractive index profile

PP-KTP waveguides

800 nm



400 nm



Multiple transverse modes supported: > 6 „red”, >25 „blue” modes for 2 μm width

Waveguide characteristics

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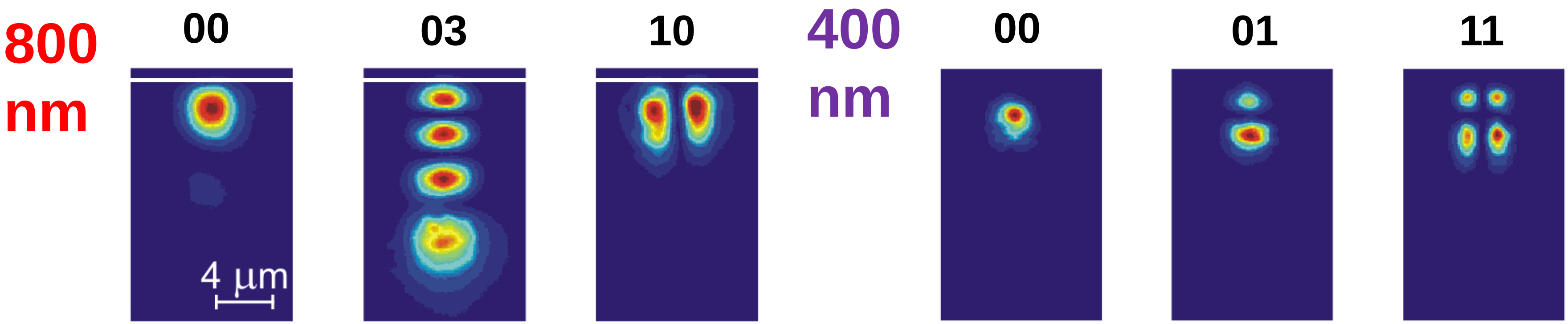
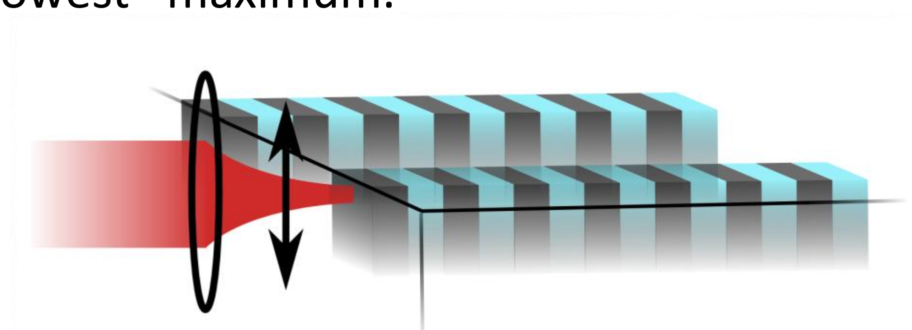
PP-KTP waveguide modes



Multiple transverse modes supported: > 6 „red”, >25 „blue” modes for 2 µm width

- Horizontally: symmetric.
- Vertically – assymetric (due to crystal-air interface & exponential refractive index profile).
- Largest fraction of power in the „lowest” maximum.

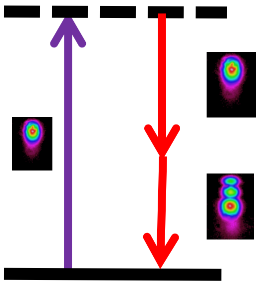
Mode selective coupling:



Spatial mode dependent phase matching

Coupling between spatial modes and phase matching
(i.e. spectral characteristics) of the three wave mixing process.

$$n_{eff}^{(j)}(\lambda) = n_{KTP}(\lambda) + \Delta n^{(j)}$$



Phase matching:

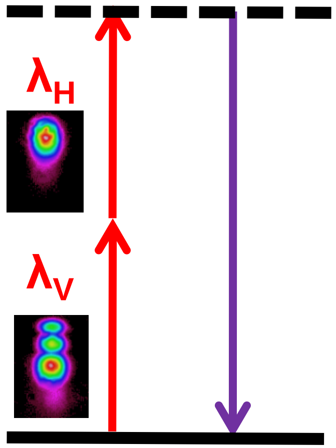
$$\Delta k = k_s + k_i - k_p - \frac{2\pi}{\Lambda}$$

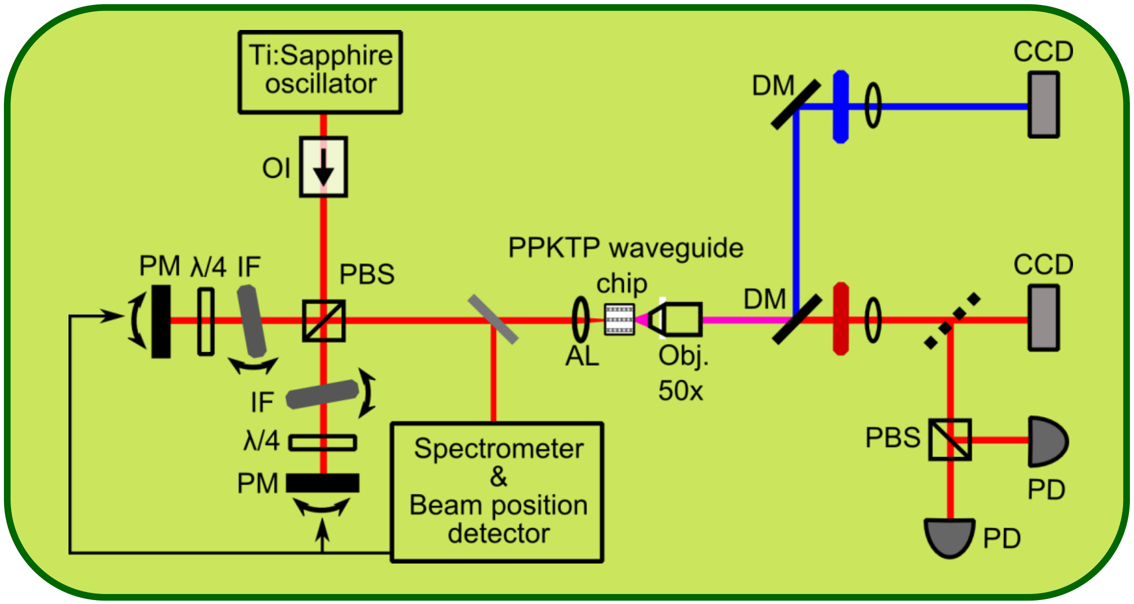
$$\Delta k^{(j,k,l)}(\lambda_s, \lambda_i) = \frac{n_s^{(j)}(\lambda_s)}{\lambda_s} + \frac{n_i^{(k)}(\lambda_i)}{\lambda_i} - \frac{n_p^{(l)}(\lambda_p)}{\lambda_p} - \frac{1}{\Lambda}$$

$$\eta^{(j,k,l)} \sim \mathrm{sinc}^2\left(\Delta k^{(j,k,l)}(\lambda_s, \lambda_i) L/2\right)$$

Spatial mode dependet phase matching condition!
Different phase matching for different spatial mode triplets (*j*, *k*, *l*) of the interacting fields.

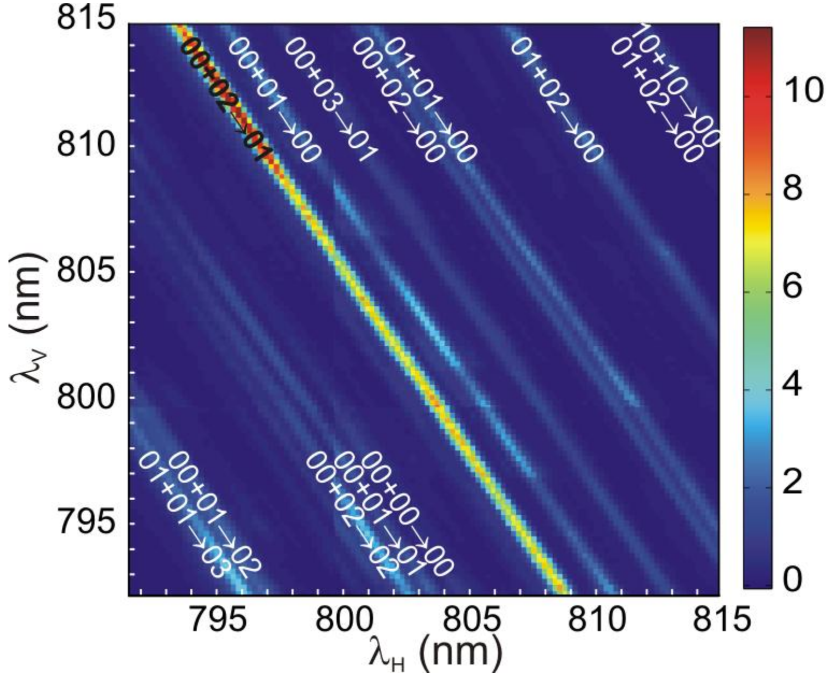
Measurement of the phase matching function



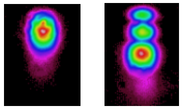


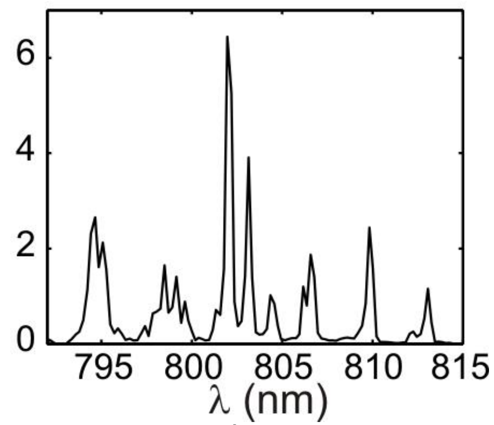
- **Type II sum frequency generation spectroscopy with spatial mode resolution (4D):**
  - wavelengths of the 2 pump fields (tuned by rotating 0,5 nm FWHM bandpass filters),
  - independent control of transverse spatial modes of the 2 pump fields,
  - active stabilization of pump beam coupling,
  - measured signal: normalized sum frequency intensity $I_{SFG}\left(\lambda_s, \lambda_i, j, k\right)$.

Measured phase matching map

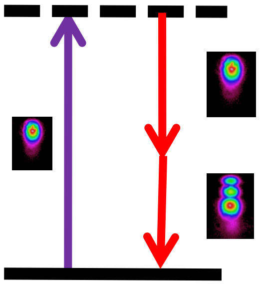


Pump beam spatial modes:



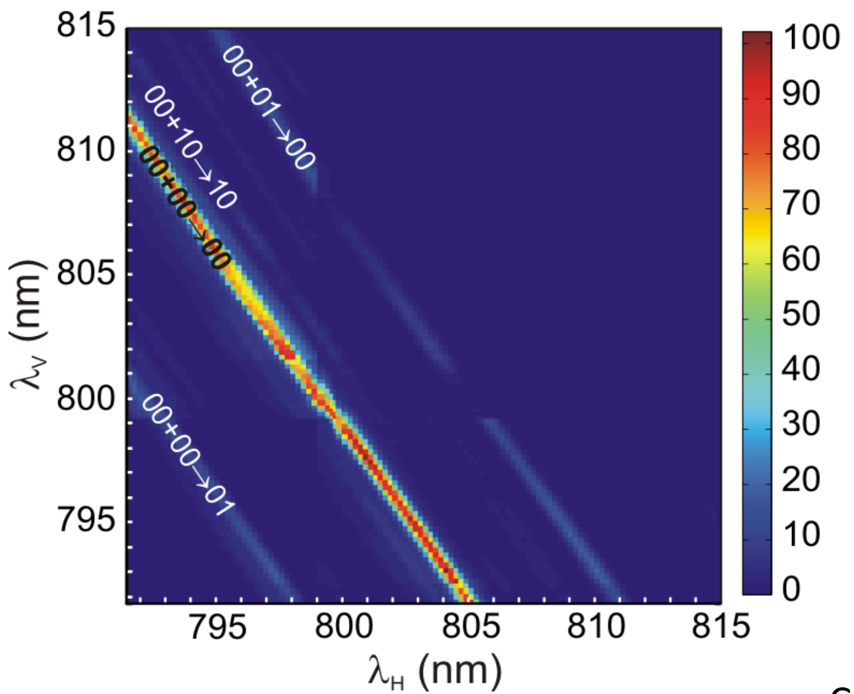


Cross section at degenerate wavelengths

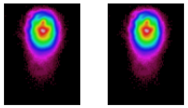


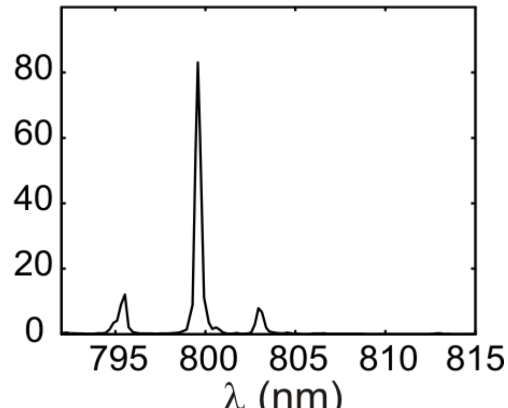
M. Karpiński, C. Radzewicz, K. Banaszek, Appl. Phys. Lett. **94**, 181105 (2009)

Measured phase matching map



Pump beam spatial modes:





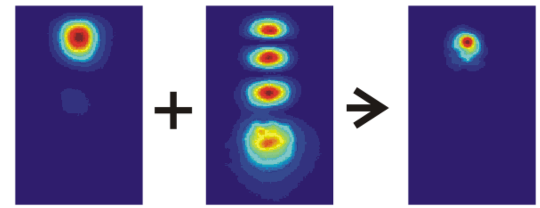
Cross section at degenerate wavelengths

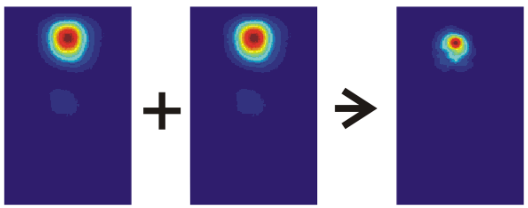
Spatial mode dependent phase matching.

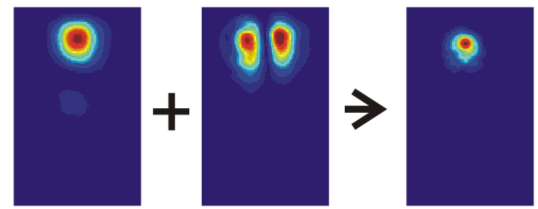
M. Karpiński, C. Radzewicz, K. Banaszek, Appl. Phys. Lett. **94**, 181105 (2009)

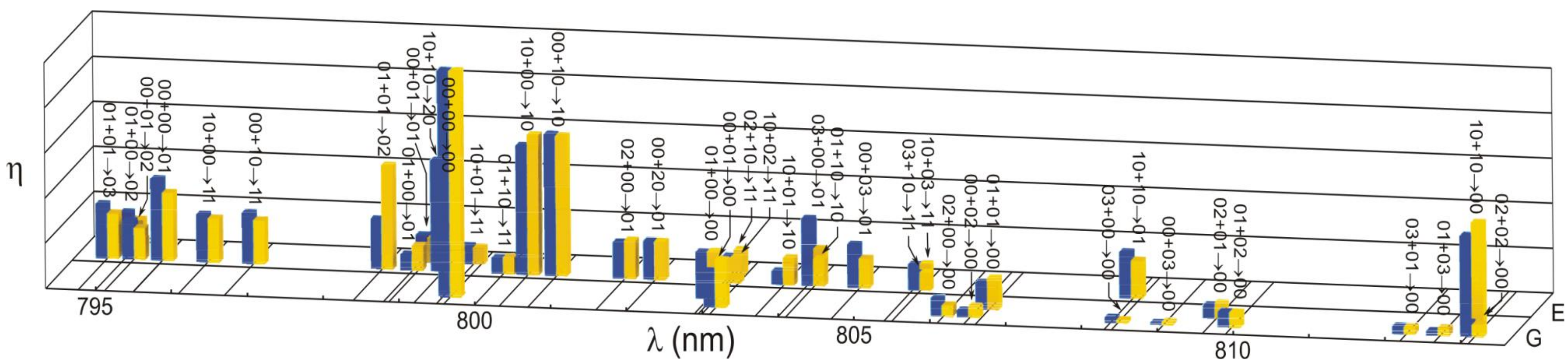
Efficiencies – mode overlap

$$\eta \sim \left(\int u_p(\vec{r}_T) u_s^*(\vec{r}_T) u_i^*(\vec{r}_T) d^2\vec{r}_T \right)^2$$





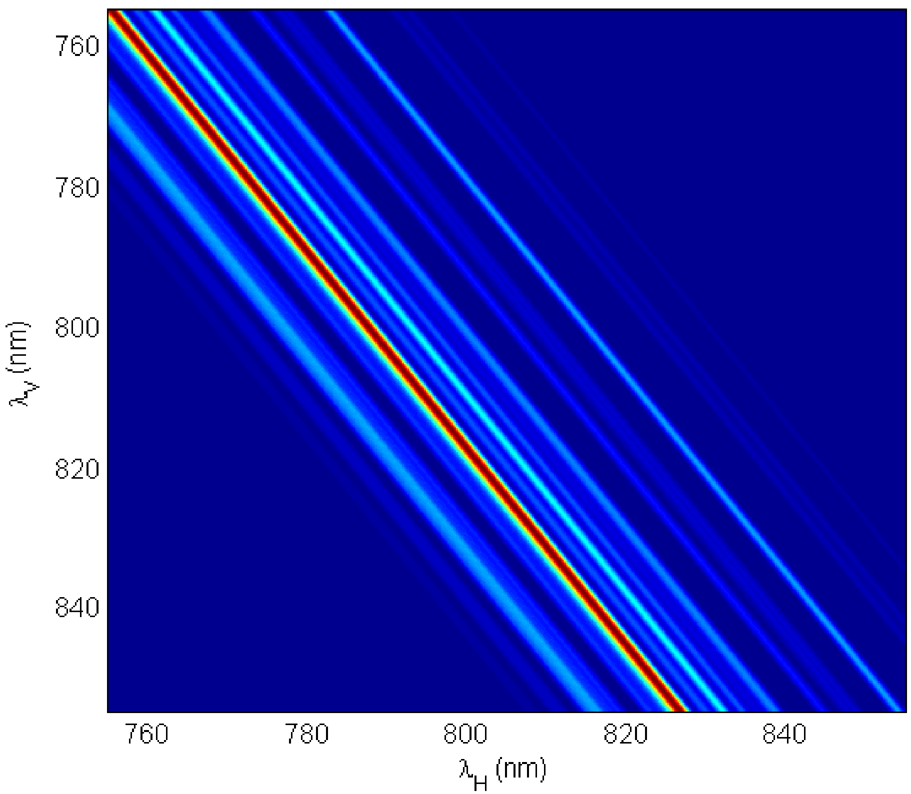


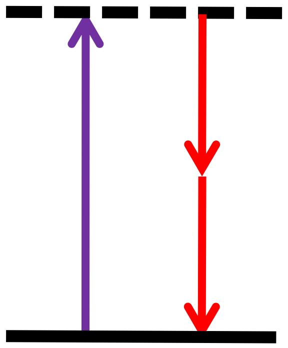


Relative efficiencies: calculated [Fallahkhair et al., J. Lightwave Tech. 26 (2008)] vs. measured.

M. Karpiński, C. Radzewicz, K. Banaszek, Appl. Phys. Lett. **94**, 181105 (2009)

Controlling the phase matching

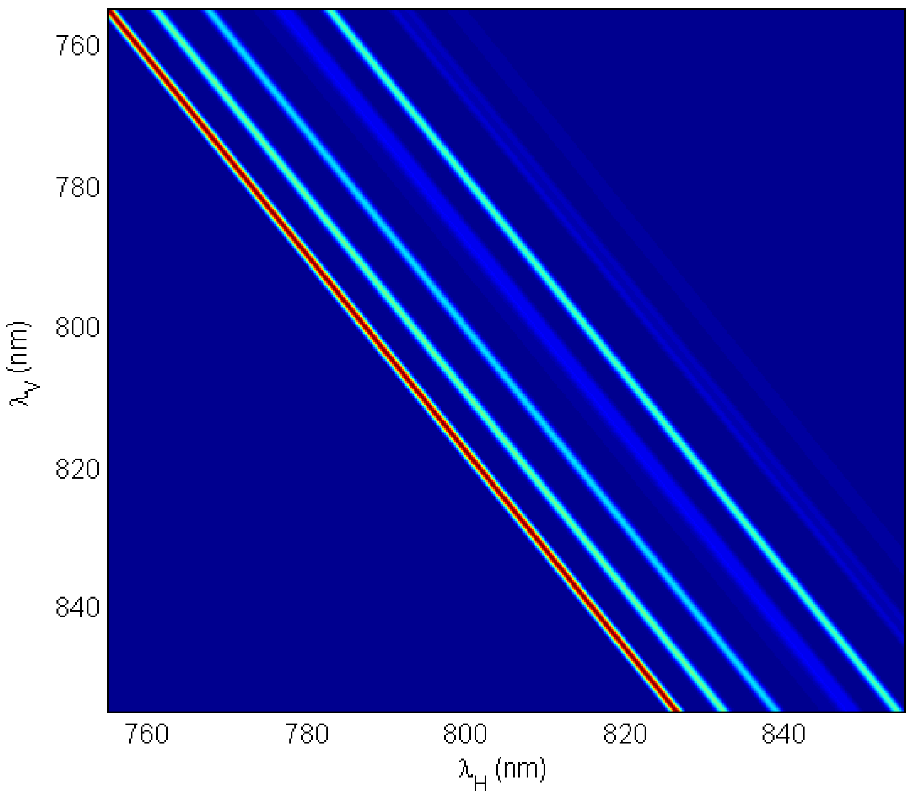




$$ij \rightarrow kl + mn$$

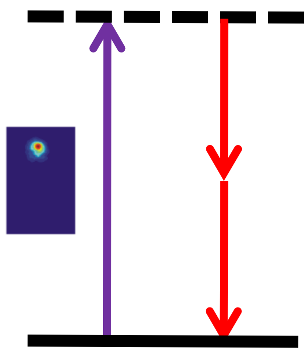
Multimode blue pump

Momentum conservation



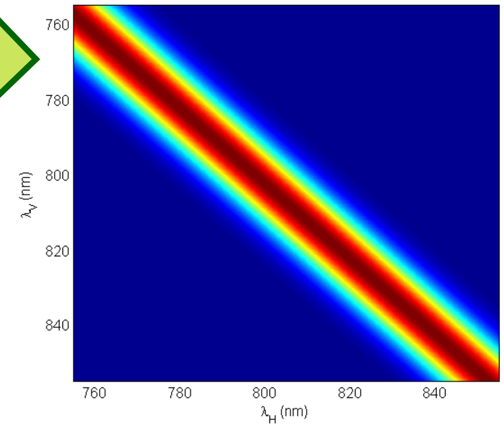
$$00 \longrightarrow kl + mn$$

Singlemode blue pump

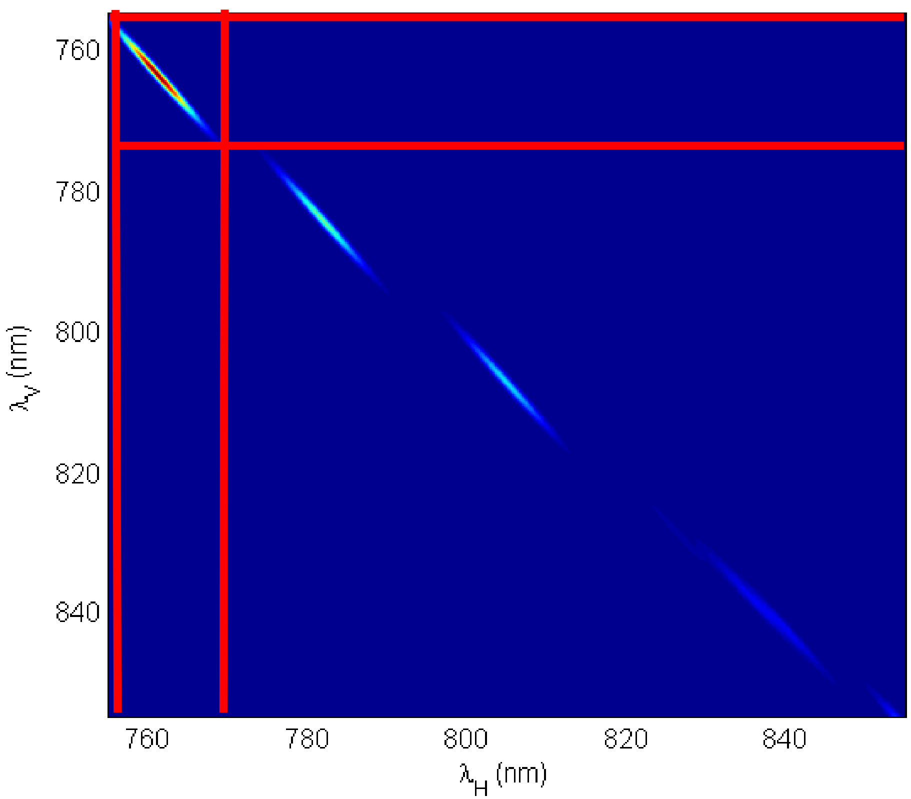


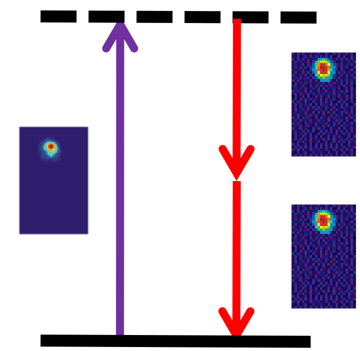
Energy conservation

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

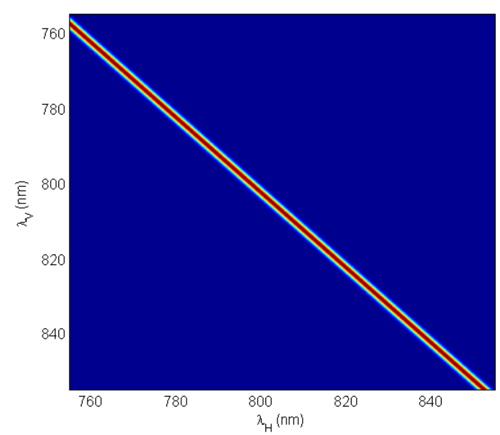


Joint spectrum





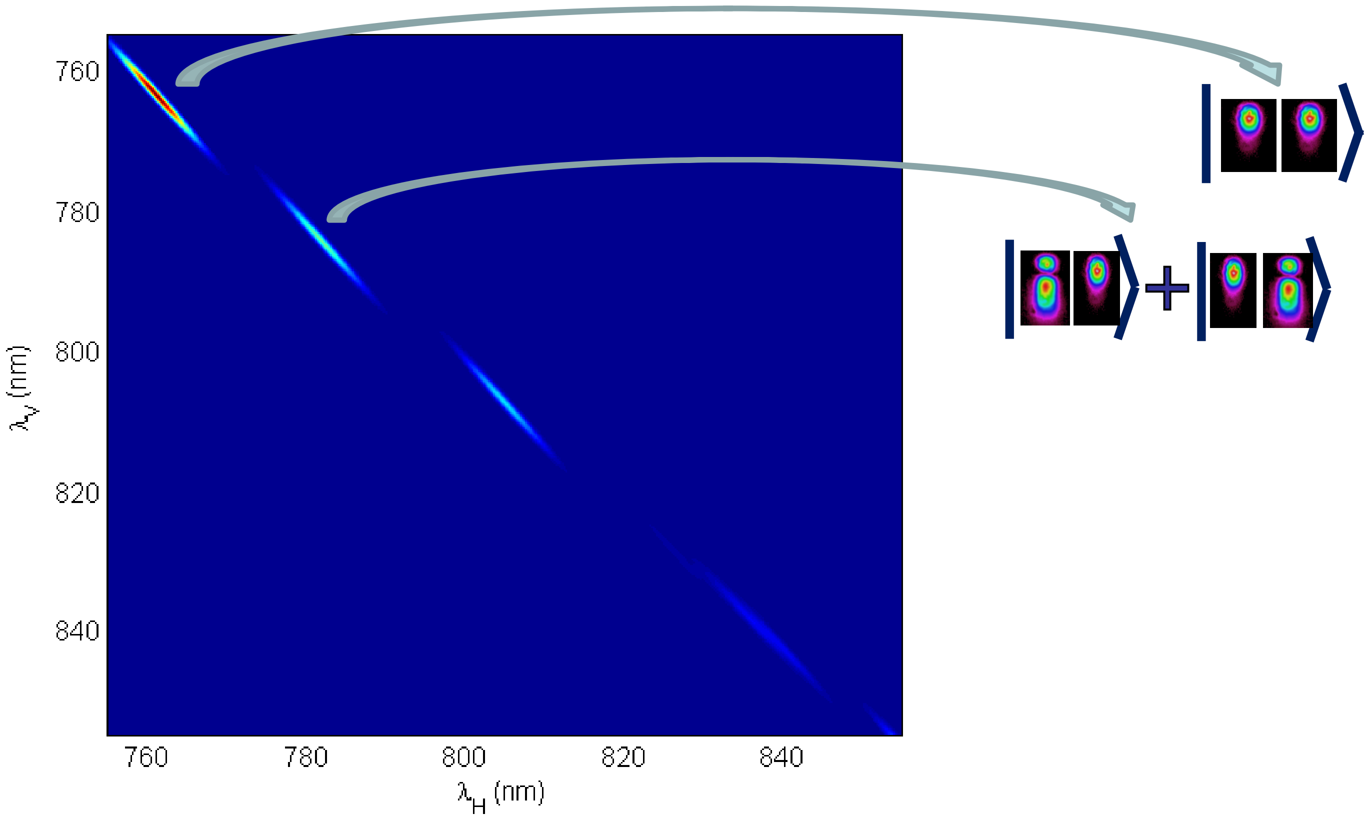
Broadband pump
Narrowband pump



$$00 \longrightarrow \bar{0}\bar{0} + 00\imath$$

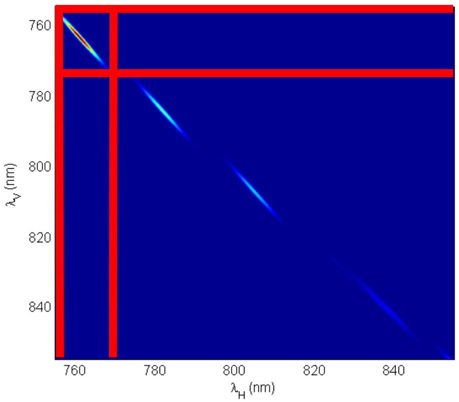
Separation of the spectral bands enables selecting well defined spatial modes

Spatial-spectral correlations



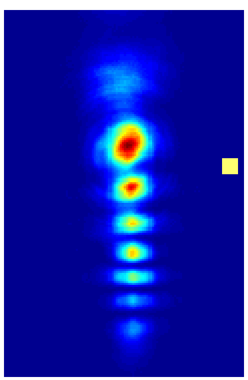
Mosley et al., Phys. Rev. Lett. **103**, 233901 (2009)

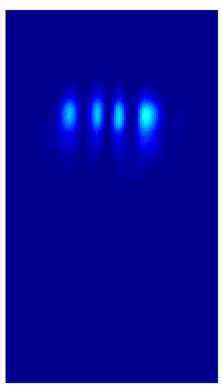
Source of spatially pure photon pairs

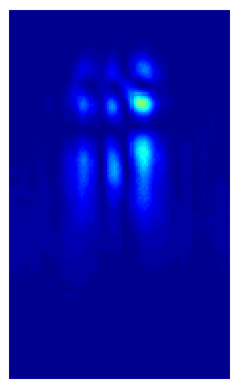


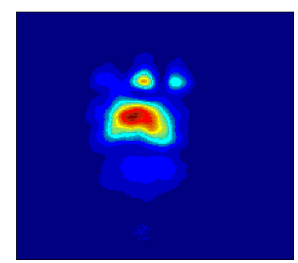
We need

- PP-KTP waveguide
- Narrowband (<2 nm) 400 nm pump
- ~10 nm FWHM spectral filtering of the downconverted field
- **Single mode blue pump!**



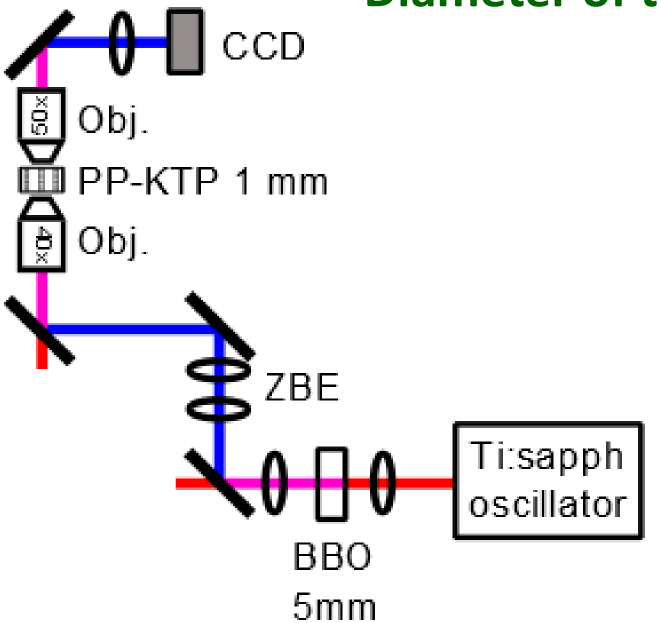


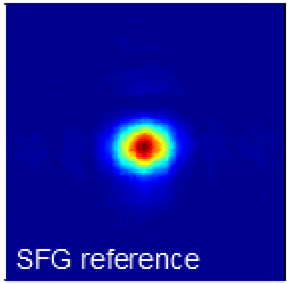


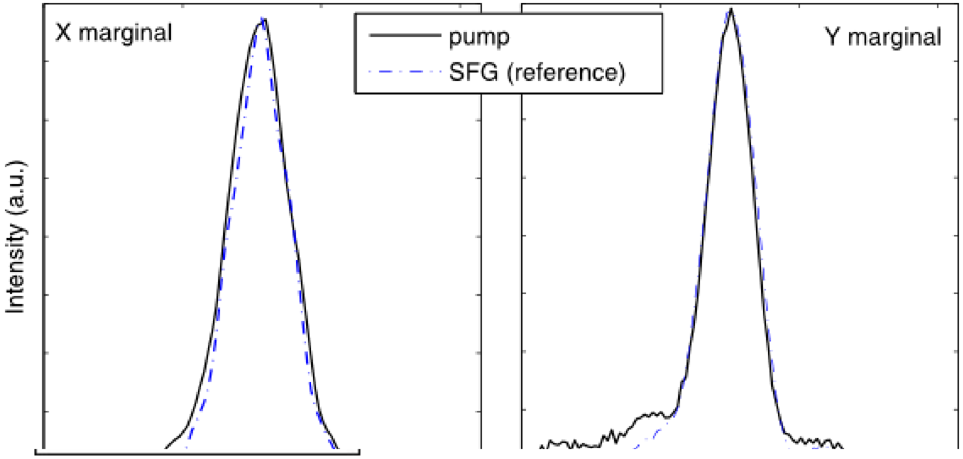


Mode-selective coupling of the pump beam

Diameter of the fundamental mode – approx. 1,3 µm

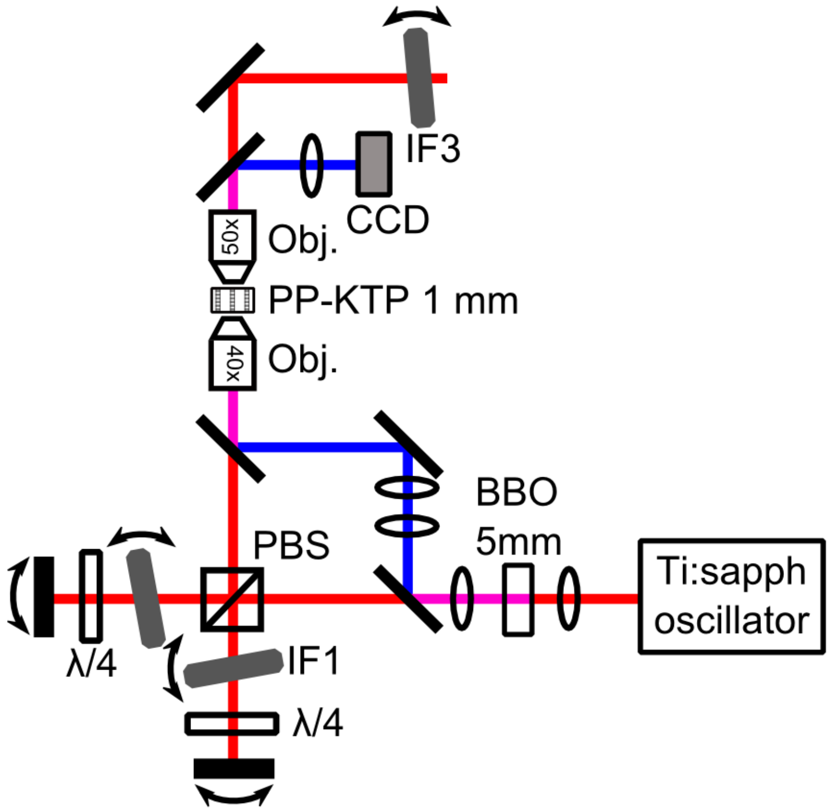




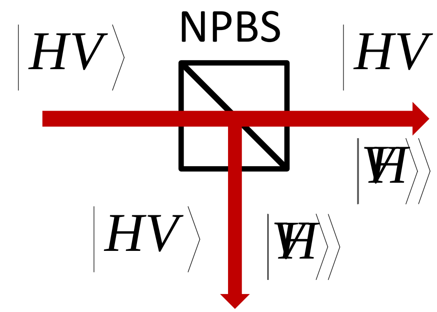


The MAX374 launch system features our high resolution differential adjusters, which are ideal for optimizing the coupling of a free space laser into a single mode fiber, even in the visible spectrum where the mode field diameter of the fibers are as small as 3 µm. The quick-release fiber holder provides six mounting surfaces

Source of spatially pure photon pairs



Test – let's entangle them:



A (postselected) entangled state

$$\frac{1}{\sqrt{2}}\left(|HV\rangle + |VH\rangle\right)$$

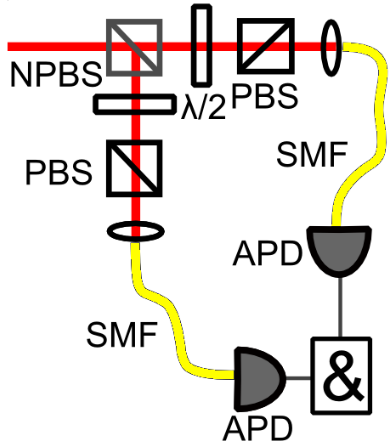
Shih, Alley PRL 61, 2921 (1988)

Correlations in HV and AD bases – **iff photons indistinguishable**

$$\frac{1}{\sqrt{2}}\left(|HV\rangle + |VH\rangle\right) = \frac{1}{\sqrt{2}}\left(|DD\rangle - |AA\rangle\right)$$

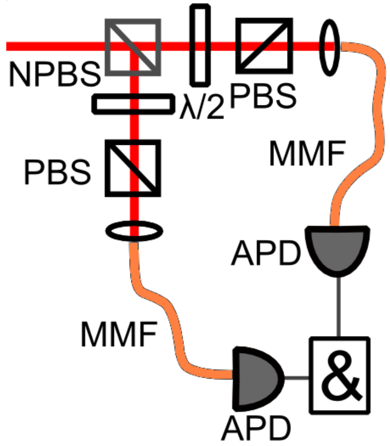
Source of spatially pure photon pairs

With spatial filtering through SMF's:



Basis	Visibility
HV	90±1%
AD	84±1%

Without spatial filtering:

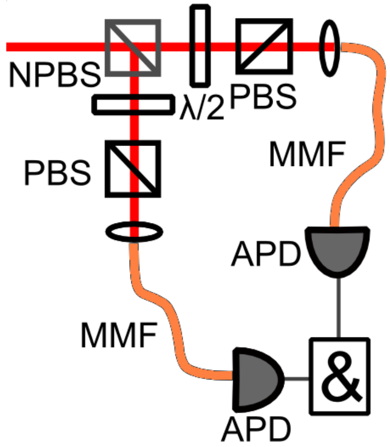


Basis	Visibility
HV	83±1%
AD	76±1%

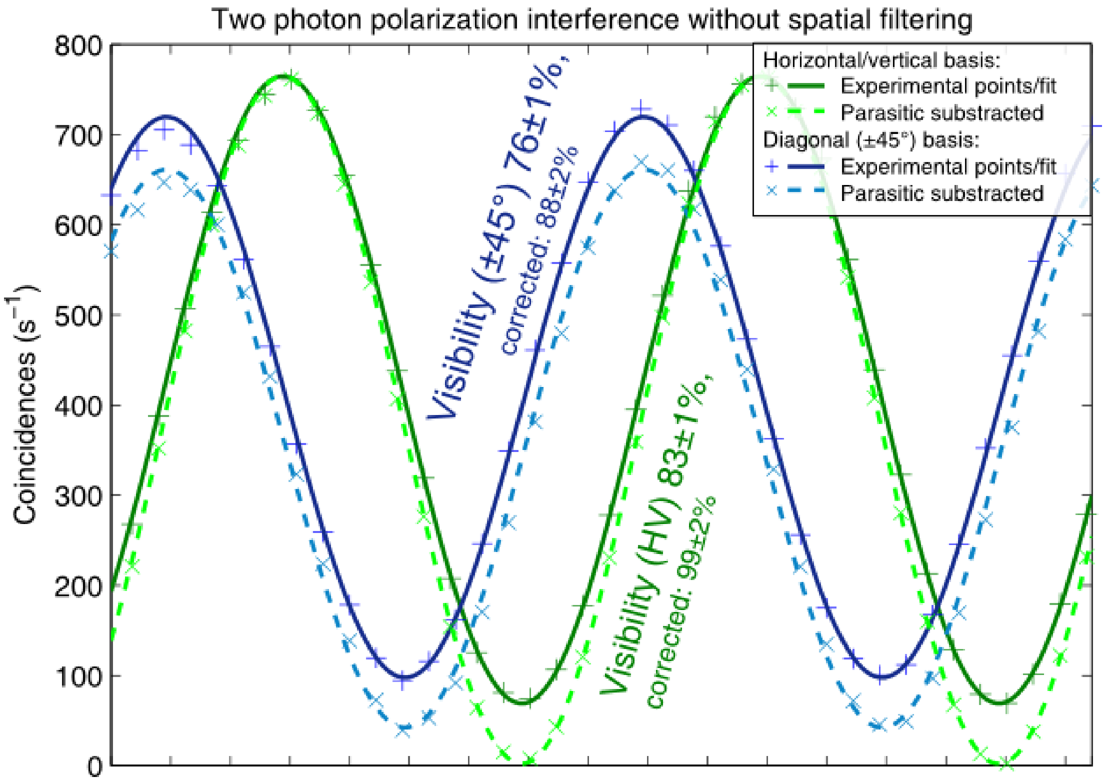
(Most probably) enables breaking Bell ineq. – with no spatial filtering

Source of spatially pure photon pairs

Without spatial filtering:

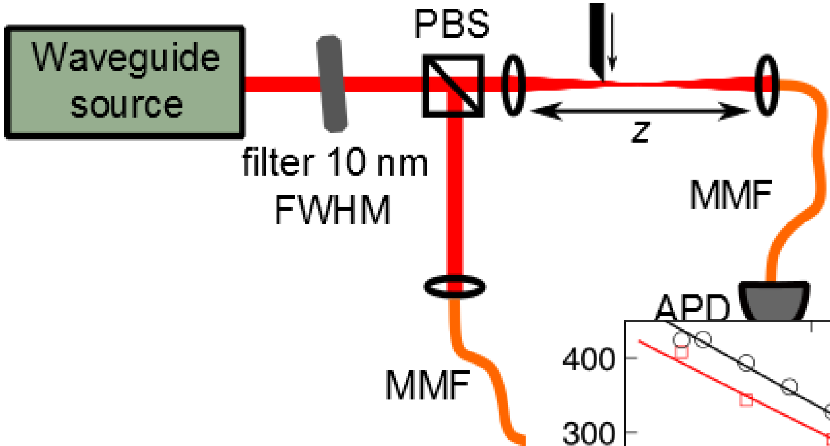


Source of visibility reduction: parasitic process delivering same polarized photon pairs.
After substracting: 100% visibility in HV basis, 88% in diagonal basis.

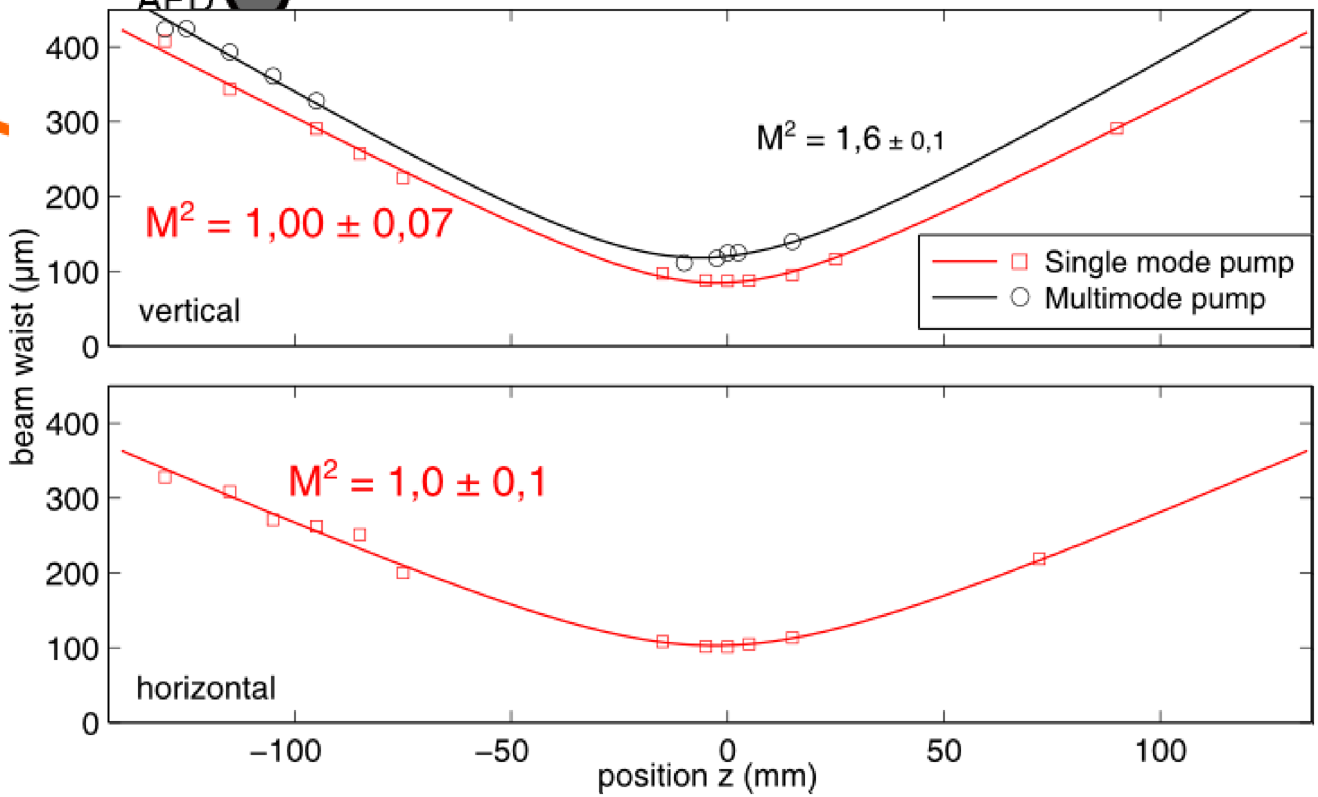


Direct measurement of beam quality

Measure M^2 beam quality factor using razor blade method

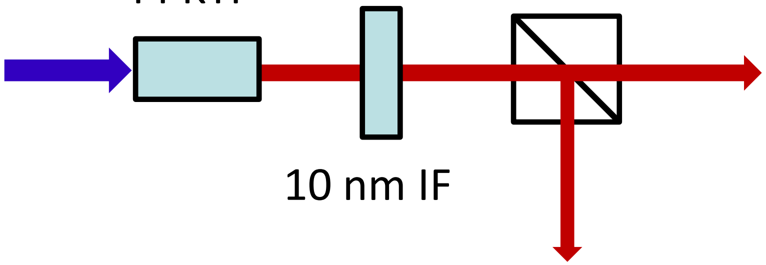


Beam propagation (horizontal/vertical):



<5% higher order mode contribution

Bright photon pair source



Blue pump power	200 μW
Efficiency of coupling the pump into the waveguide	25-45%
Single counts	$1{,}2 \cdot 10^5\ s^{-1}$
Coincidences	$1{,}5 \cdot 10^4\ s^{-1}$
Coincidences/singles (@19% detection efficiency)	12%
Coincidences/singles assuming 100% detection efficiency.	>60%
SMF coupling efficiency	>57%

Summary

- Measurement of mode dependent phase matching in PP-KTP waveguides,
- Spectral control of transverse modes in downconversion,
- Entanglement without spatial filtering,
- Efficient photon pair generation.
- Future: efficient generation of spatial mode entangled and hyperentangled states.

Thank you for your attention

Ultrafast Phenomena Lab

National Laboratory for Atomic, Molecular and Optical Physics

Support: Team Programme (TEAM) – Grants for Innovations

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NATIONAL COHESION STRATEGY

FNP
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