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for Extreme and Quantum Photonics

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Towards a waveguide source of polarization-entangled photons: Photon pair generation in fiber microcouplers

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CAP Congress, June 15, 2016

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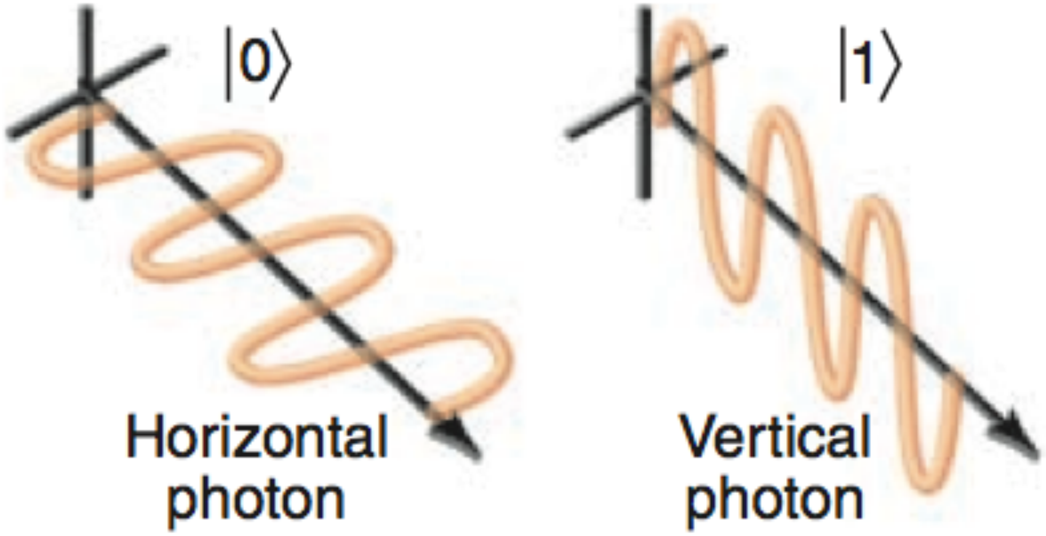
Introduction

- Quantum optical computer
  - Need source of entangled photon pairs
- Polarization entanglement example:
  - For singlet state: $|H_1V_2> - |V_1H_2>$

    if measure photon 1 to be H,

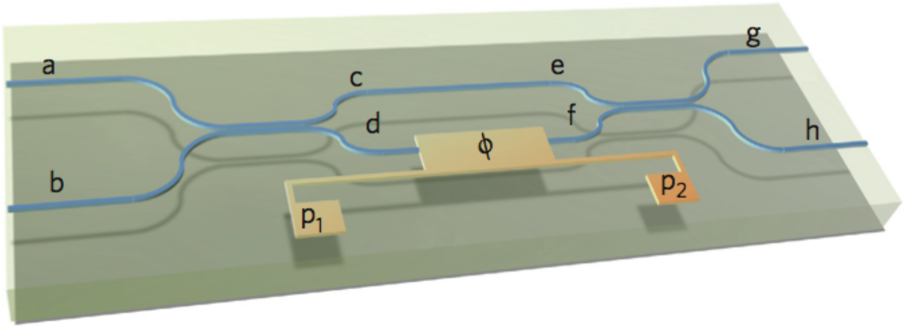
    know photon 2 is in V



J. L. O'Brien, *Science* **318**, 1567 (2007);

Introduction

- Integrate photonics: microchips[1,2]
  - mostly using free-space, off-chip photon source: the number of photons carried by the device is limited by the mismatch between the generated modes and modes of the chip



Matthews, J. C. F. et al. Nat. Photon. (2009).

- Advantage of a fiber-based source:
  - can avoid mode mismatch, reduce loss[3,4]

photons are generated in fundamental mode of fiber, well-matched with waveguide mode of optical chips

1. Matthews, J. C. F. et al. *Nat. Photon.* **3**, 346–350 (2009).
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3. K. Garay-Palmett, et al. *Opt. Express* **15**, 14,870–14,886 (2007).
4. B. Smith, et al. *Opt. Express* **17**, 23589-23602 (2009).

Spontaneous four-wave mixing (SFWM)

- Phasematching:

Achieve energy and momentum conservation

$$E = \hbar\omega$$

$$p = \hbar k$$

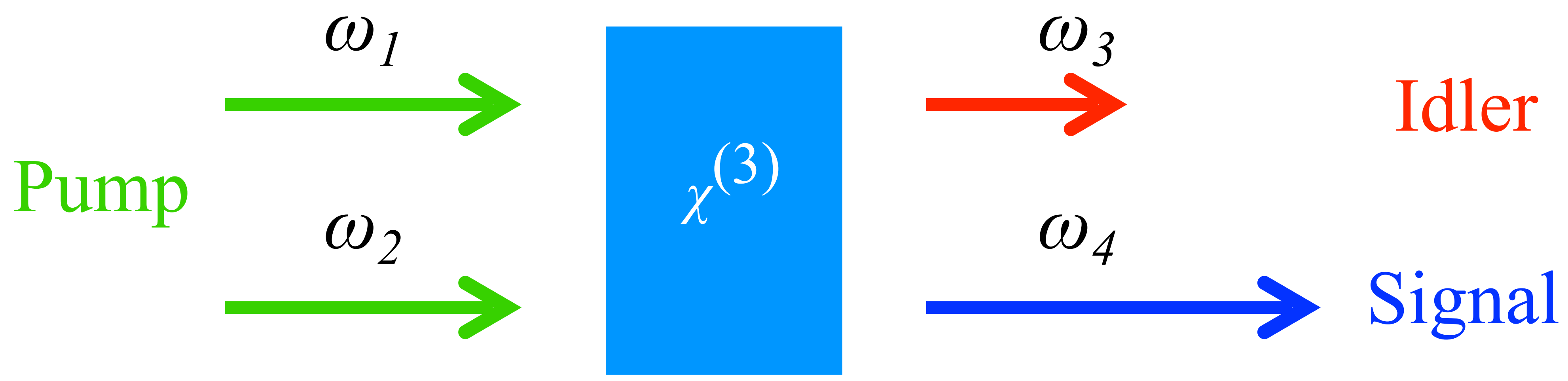
$$\omega_3 + \omega_4 = \omega_1 + \omega_2$$

$$\Delta k = k_3 + k_4 - k_1 - k_2 = 0$$

$$k_i = n_i\,\omega_i/c$$

$$\downarrow$$

$$n(\lambda)$$



Microcoupler

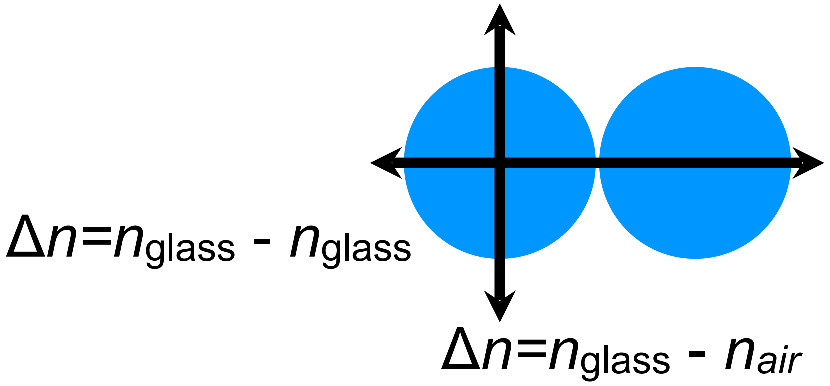
- Structure:

  10cm long uniform interaction region with 1 micron diameter;

  fabricated with two identical single mode fibers (SMFs) heated and stretched while kept in contact

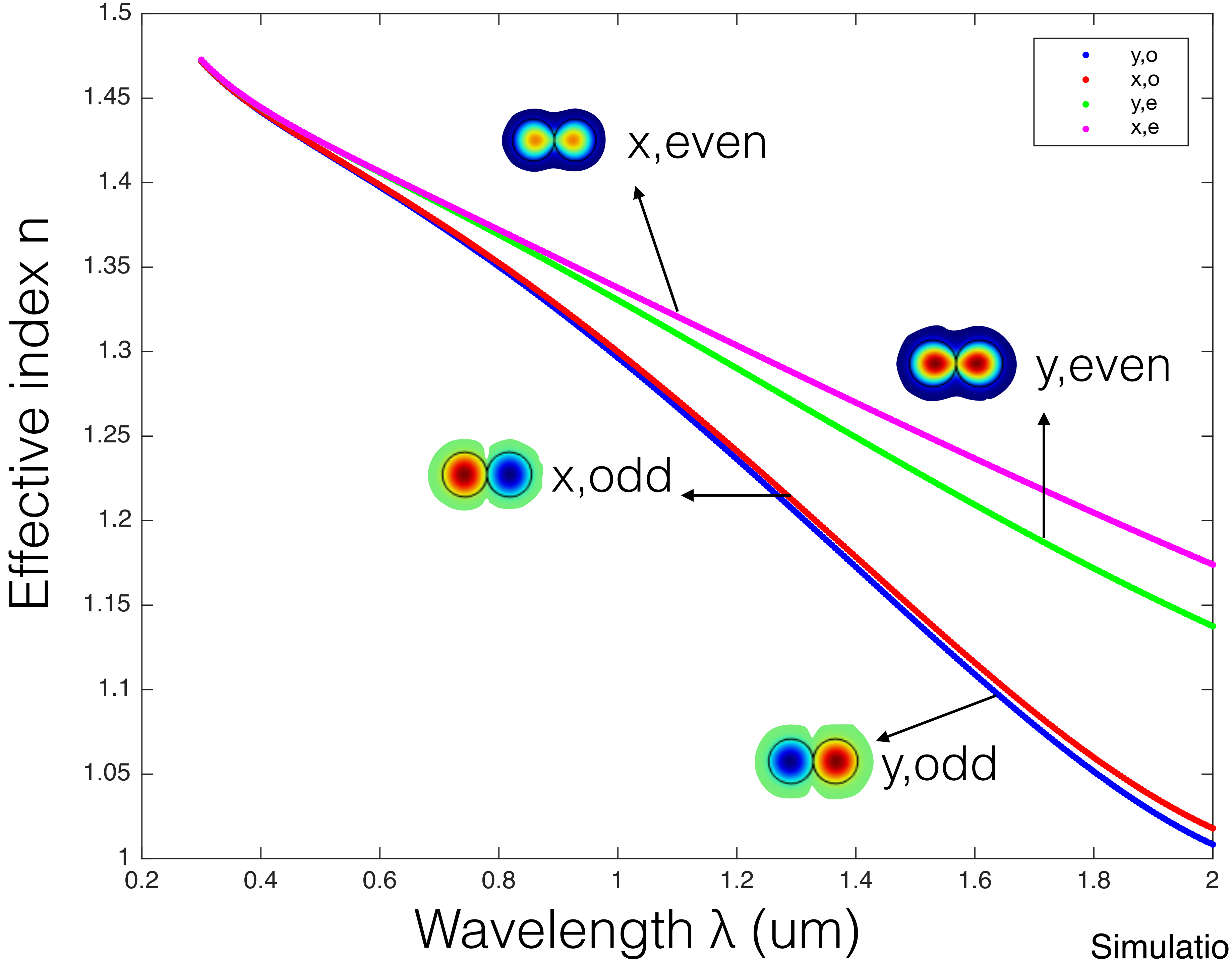
- Coupling of 4 modes in 2 cores - minimum number of modes required for entanglement

- Different indices for each mode



Simulation: effective index vs. wavelength

Effective index vs. wavelength for microcoupler *n(λ)*



$$\Delta k = k_{\mathrm{x,o}} + k_{\mathrm{y,o}} - k_{\mathrm{x,e}} - k_{\mathrm{y,e}}$$

$$= 0$$

$$k_i = n_i \, \omega_i / c$$

Simulation results courtesy of Jefferson Flórez

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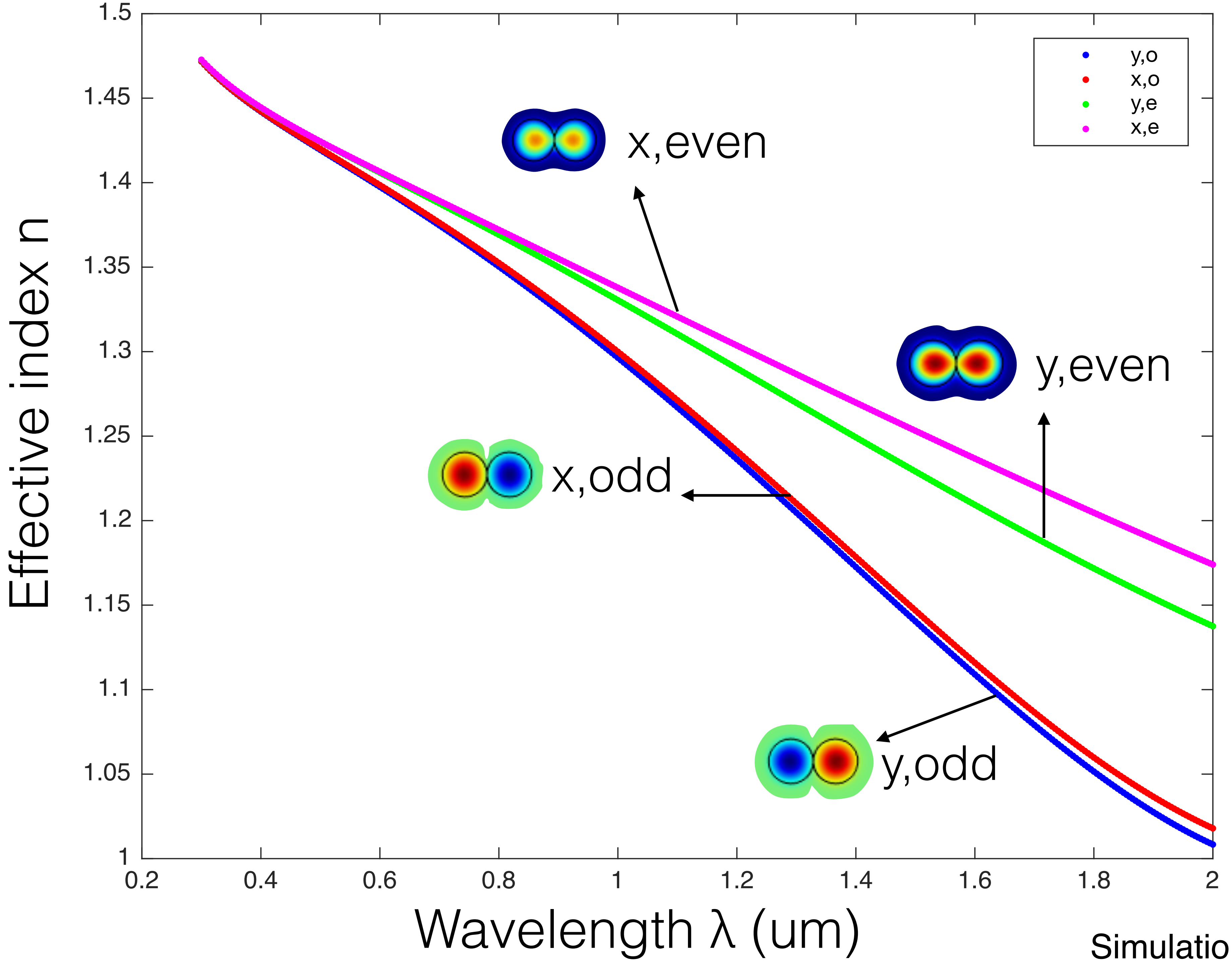

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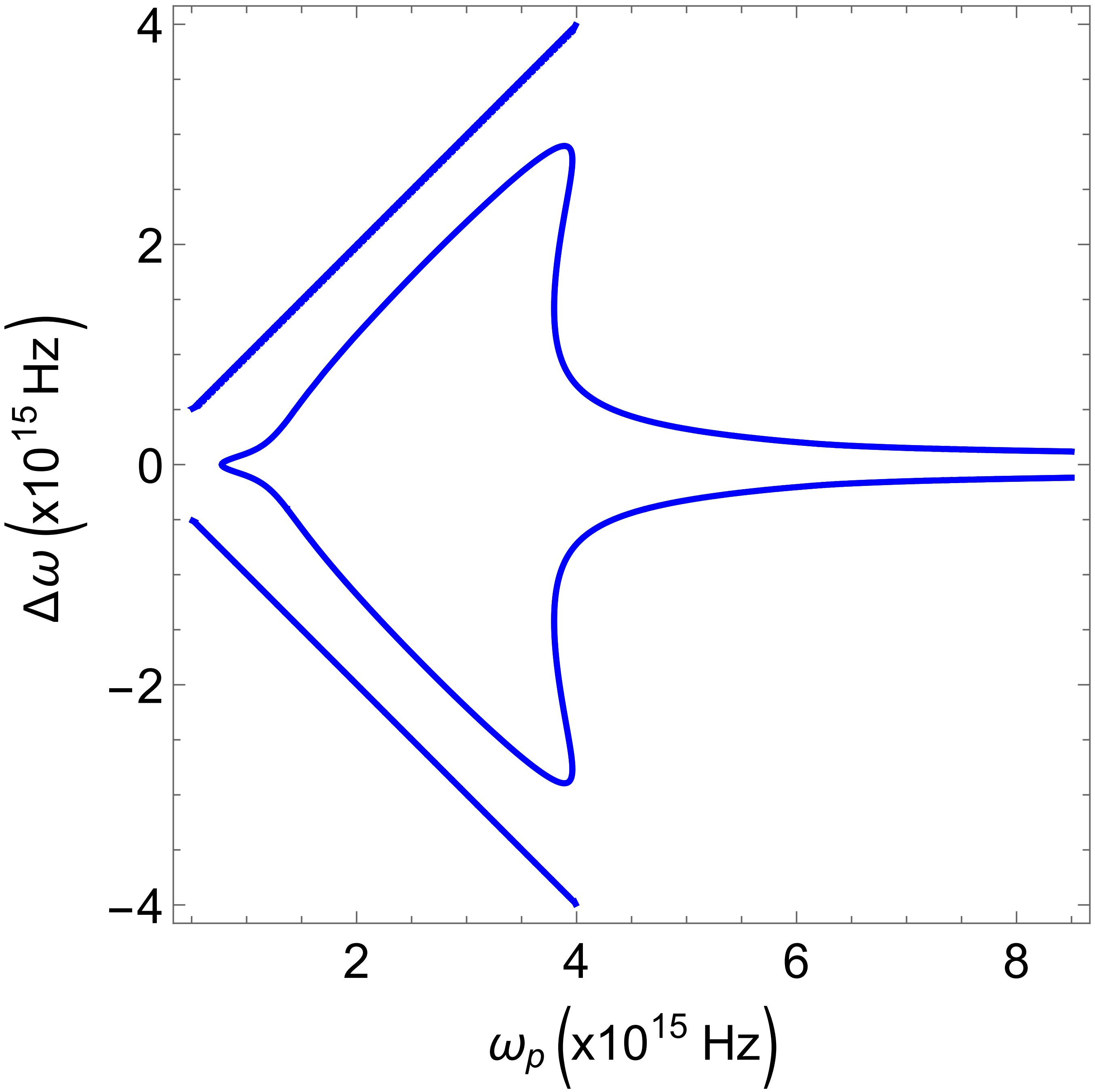
Use n(λ) to find k and solve phasematching equation to predict the location of SFWM photon pairs

Simulation results courtesy of Jefferson Flórez

Phasematching contour plot

Frequency splitting vs. pump frequency

$$\Delta k = k_{\mathrm{x,o}} + k_{\mathrm{x,o}} - k_{\mathrm{y,o}} - k_{\mathrm{y,o}} = 0$$



- Three frequencies in phasematching contour plot: ω_s and ω_i split symmetrically from ω_p

- Need to find ω_s-ω_p for each possible phasematching situation for microcoupler

Phasematching

- **28** combinations allowed for microcoupler: all cases where only one mode is different from the other three cannot happen[1]

- for example: x,e + y,o —> x,e + y,o is allowed,

but not x,e + y,o —> x,e + x,e

$$\boxed{\Delta k = k_{\mathrm{x,o}} + k_{\mathrm{y,o}} - k_{\mathrm{x,e}} - k_{\mathrm{y,e}} = 0}$$

Entanglement possible: If these two processes below produce photons at the same wavelength, we will get entanglement:

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1. G.Agrawal, *Nonlinear Fiber Optics* (2013).

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xe+yo—>xe+yo
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Entanglement possible: If these two processes below produce photons at the same wavelength, we will get entanglement:

xe+yo—>xe+yo
xo+ye—>ye+xo

Input state is like the Singlet State: lxe yo>+lxo ye>,
if measure even photon to be x, know odd photon is y

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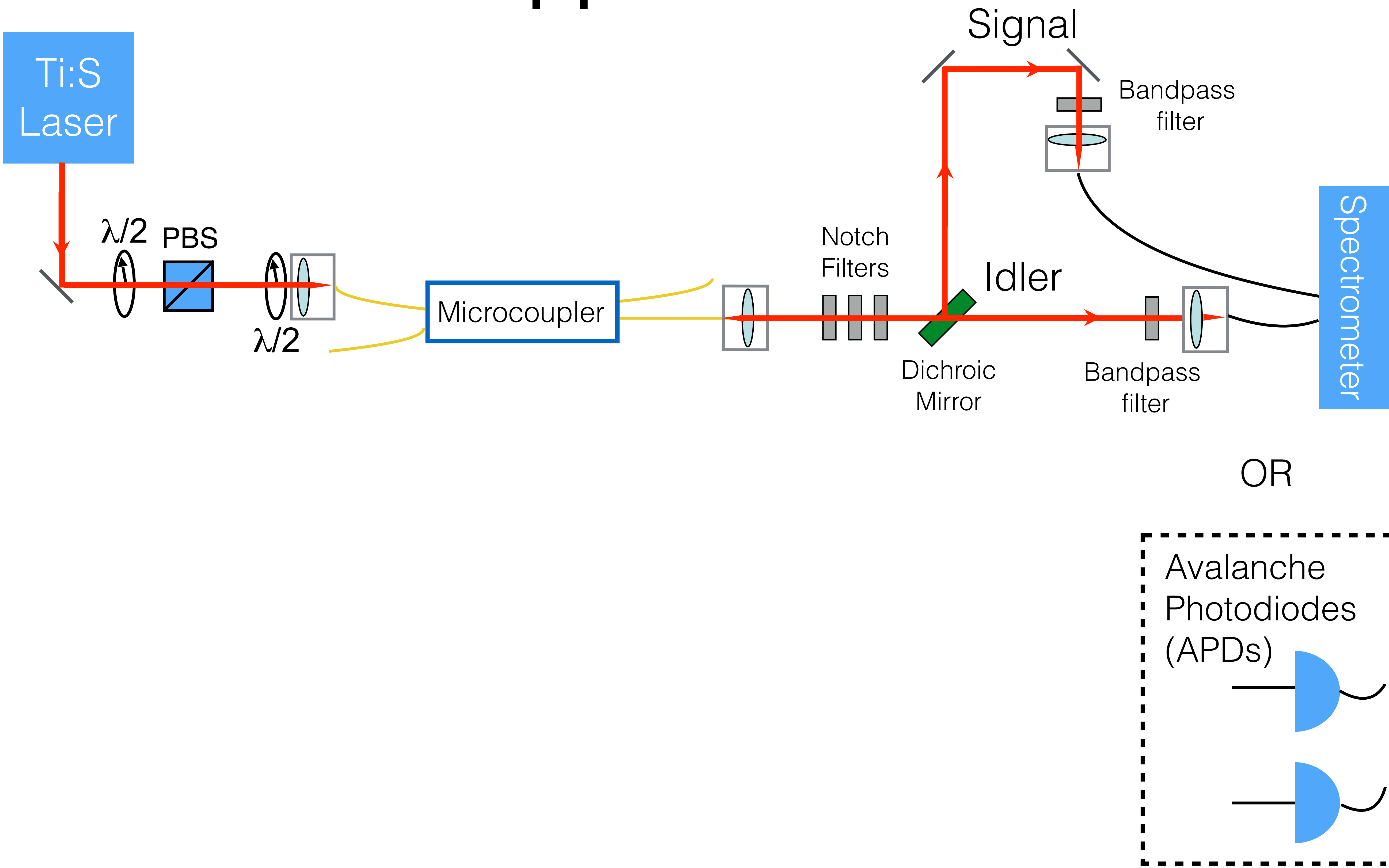
1. G.Agrawal, *Nonlinear Fiber Optics* (2013).

Apparatus



Ti:S Laser

λ/2

PBS

λ/2

Microcoupler

Notch Filters

Dichroic Mirror

Signal

Bandpass filter

Idler

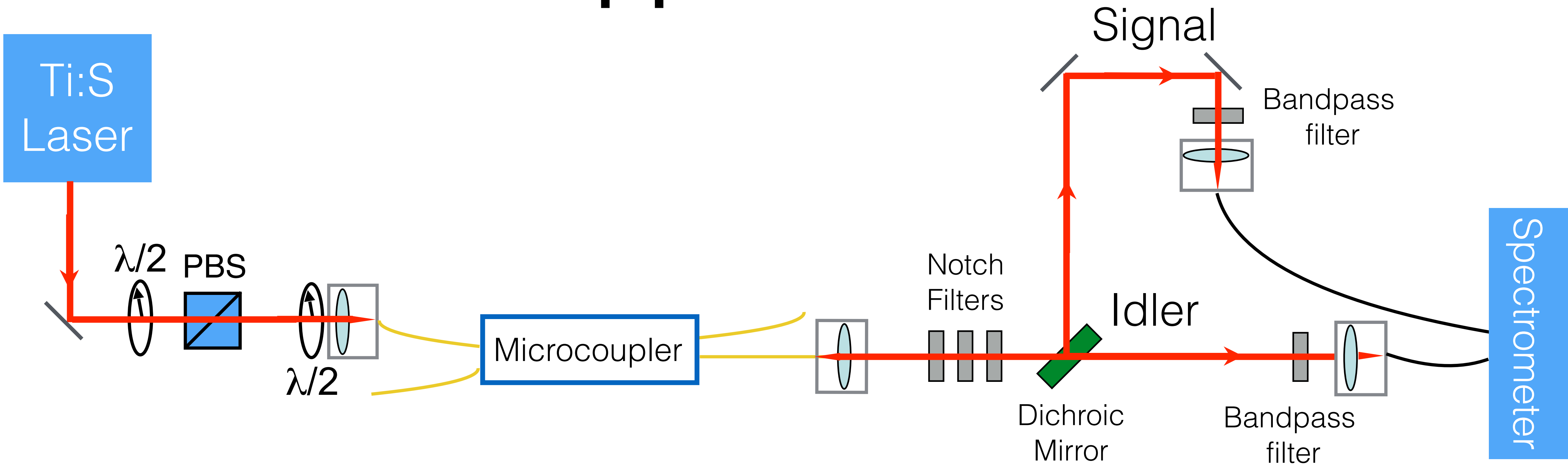
Bandpass filter

Spectrometer

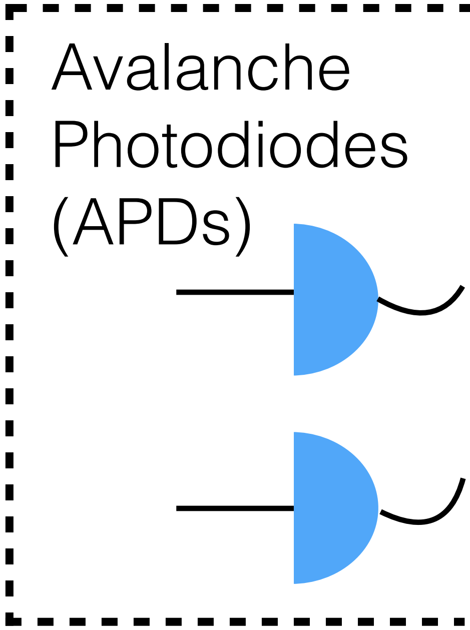
OR

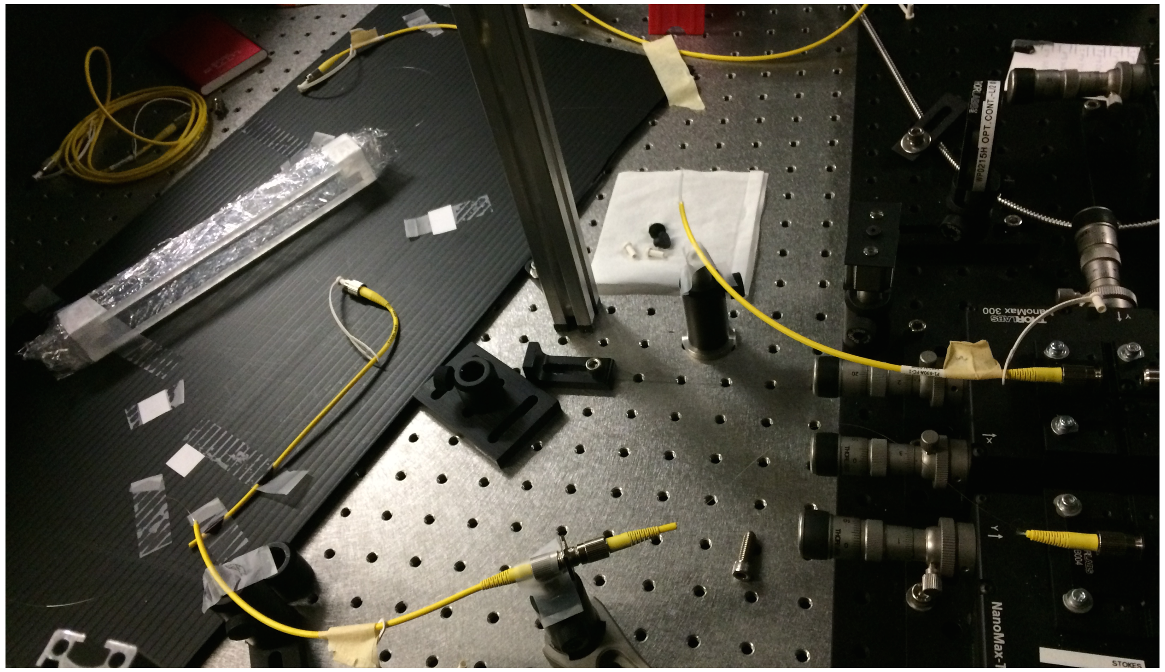
Avalanche Photodiodes (APDs)

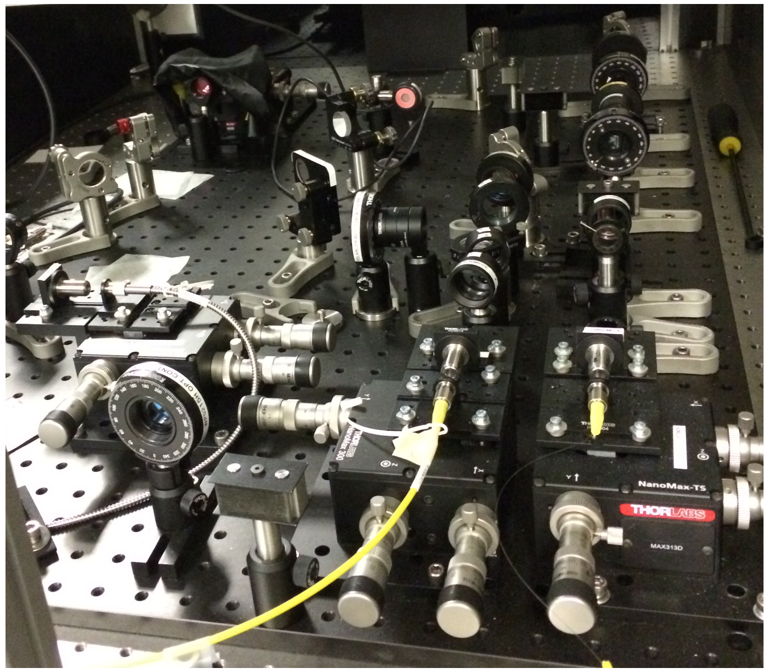
Apparatus



OR

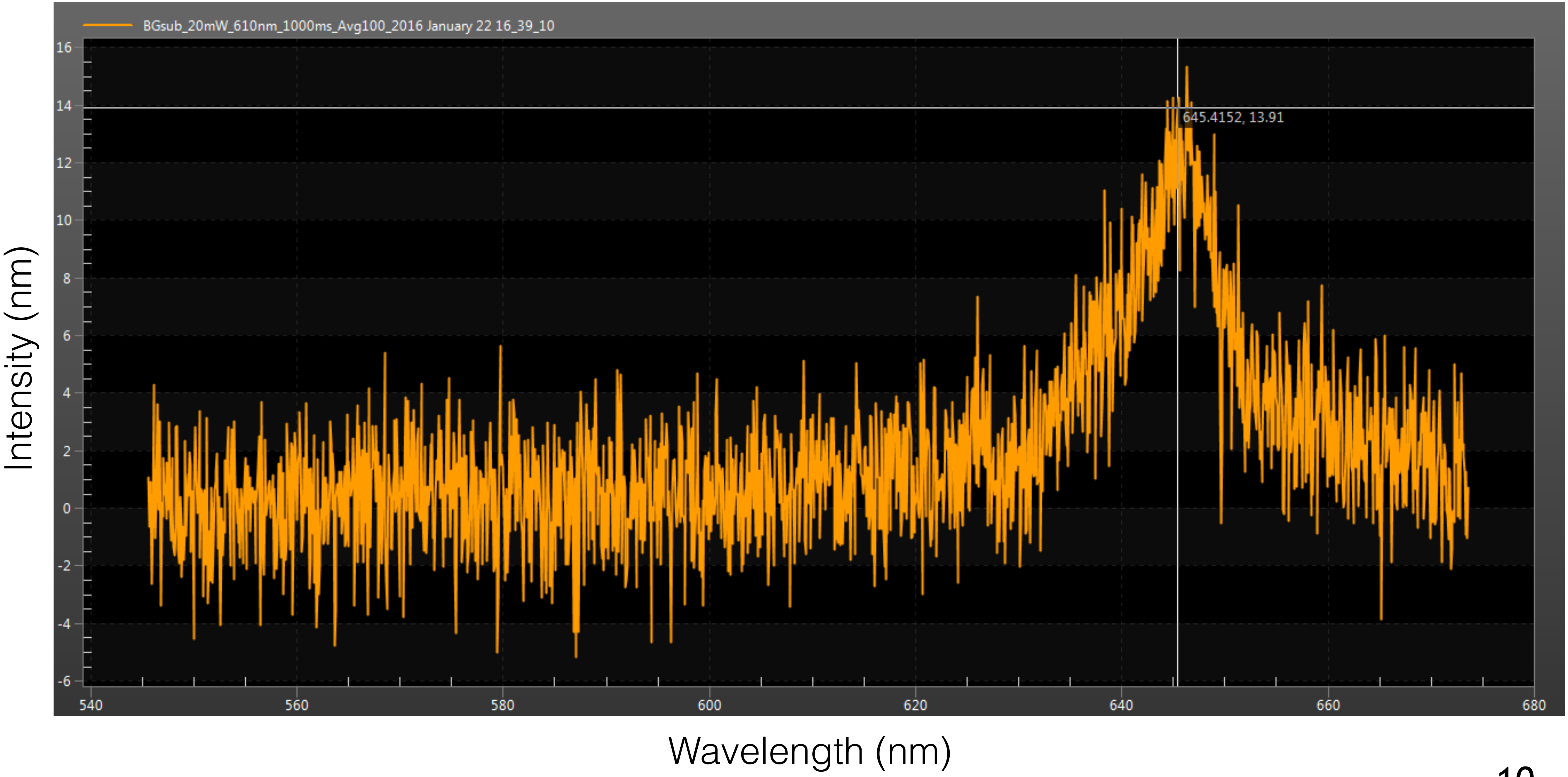






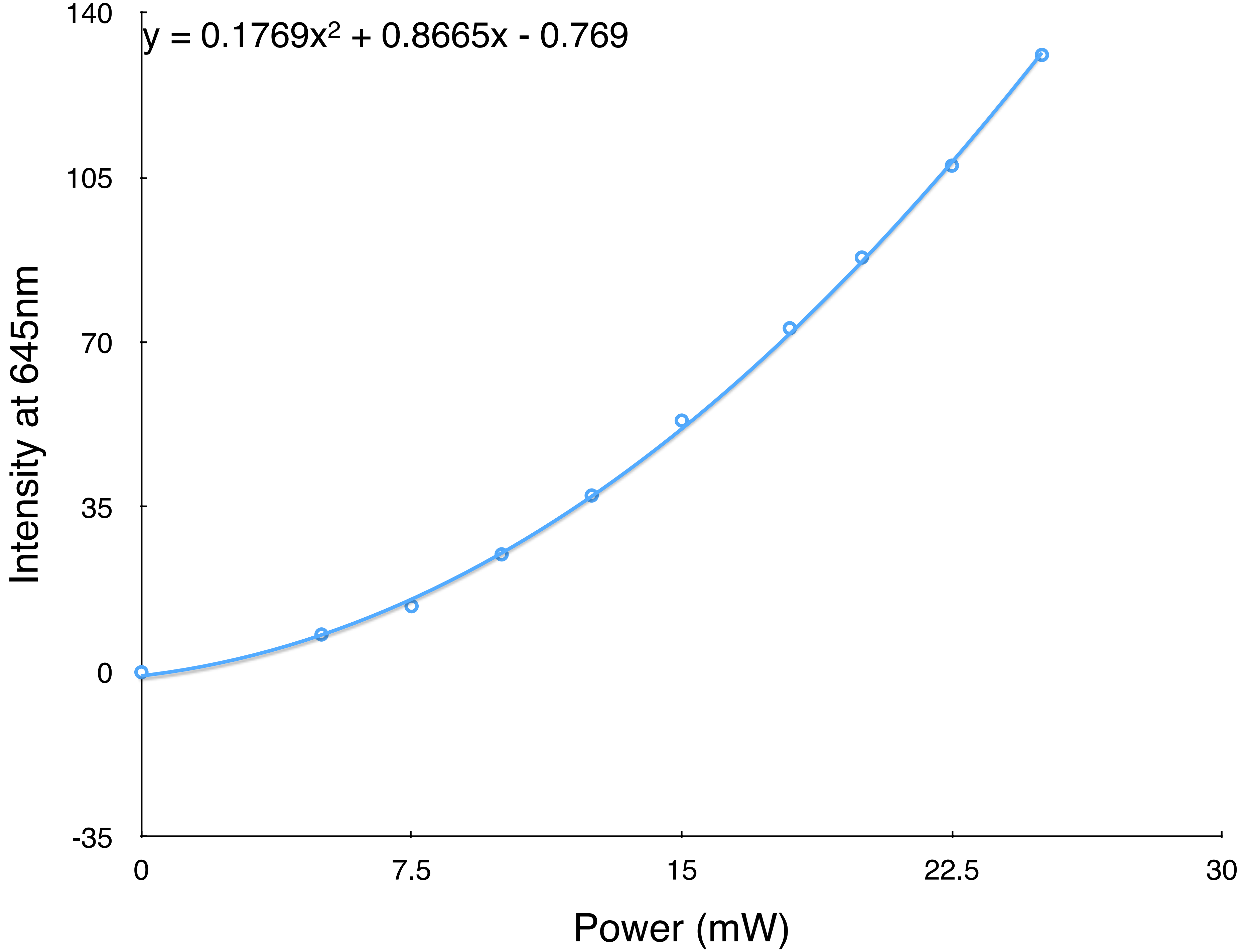
Results: SFWM peak in microcoupler

- Microcoupler with 1 micron diameter, 10cm interaction length



Pump power dependence of 645nm signal peak

Intensity vs. input power, 645nm 3000ms Avg100 frames



Quadratic power dependence as expected for photons created via SFWM (would be linear if due to Raman noise)

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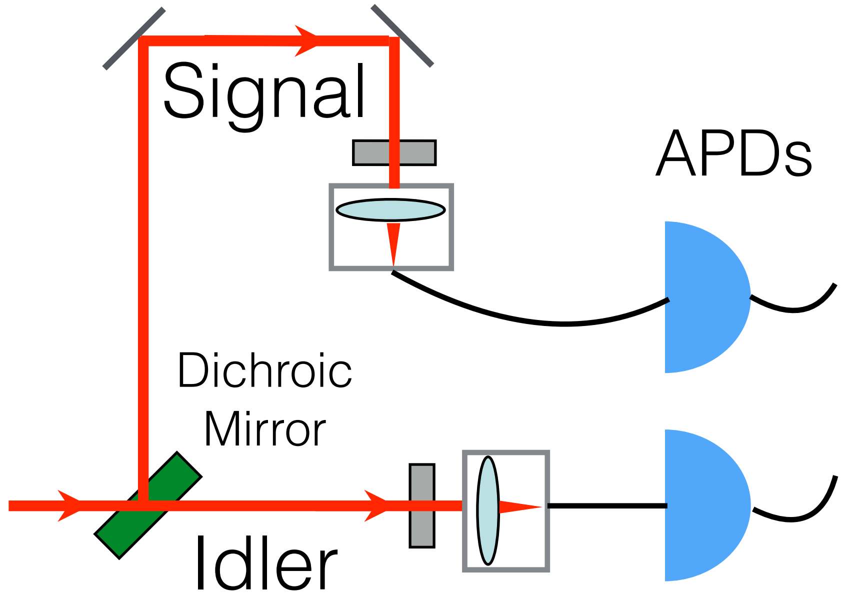
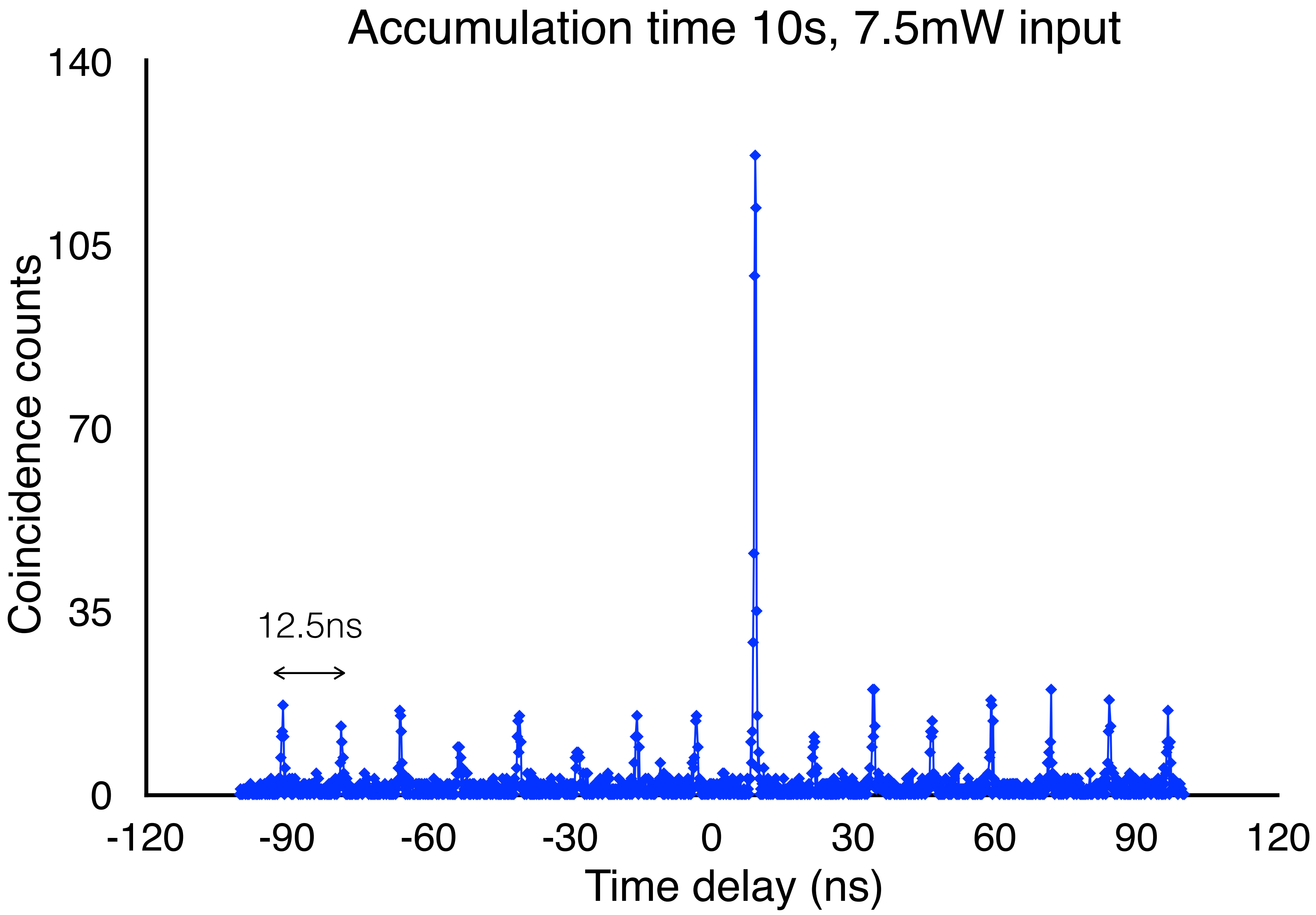
SFWM photon pair: histogram data





Confirmed SFWM photon pair generation:
signal photon at 645nm,
idler photon at 1053nm

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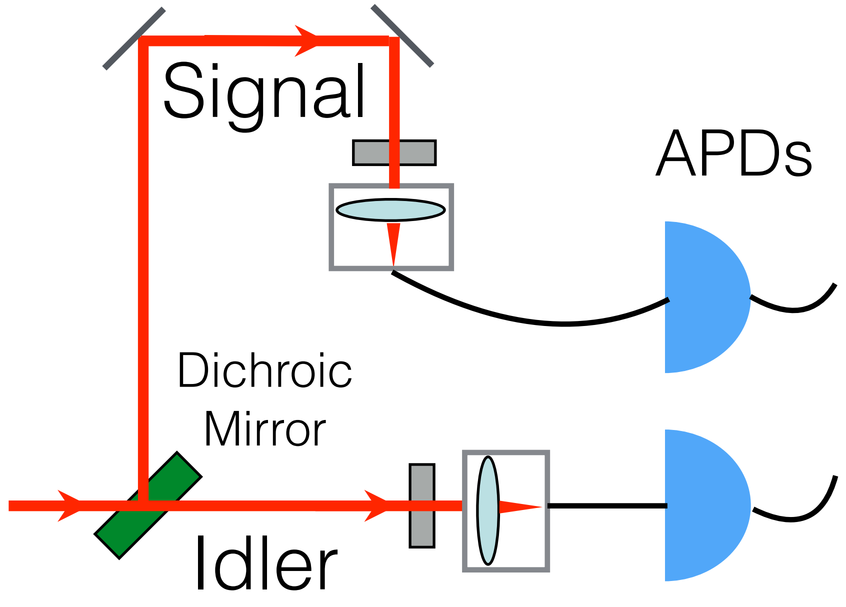

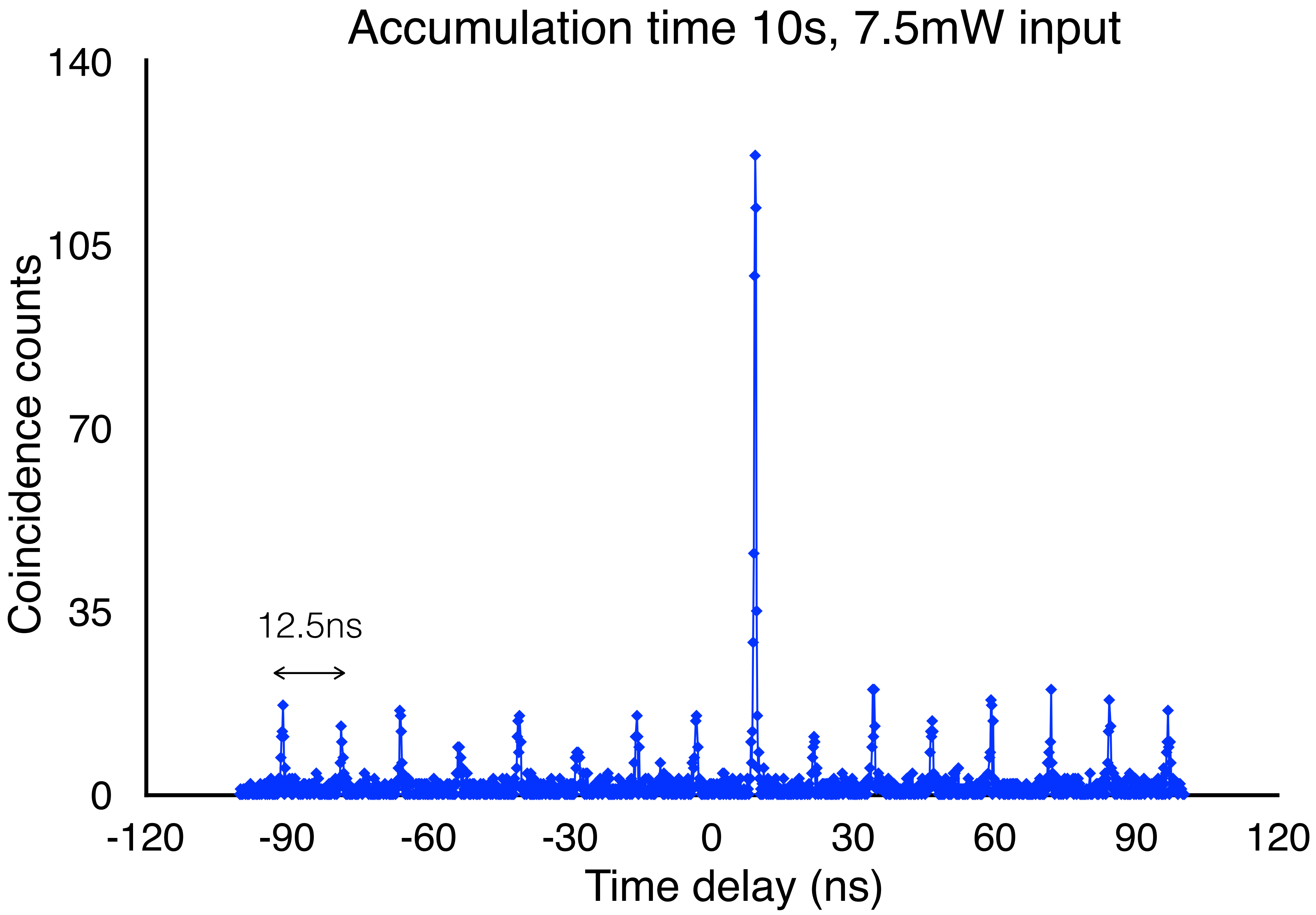

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Analyzed polarization of signal and idler photons: orthogonal with overlap = 0.1738

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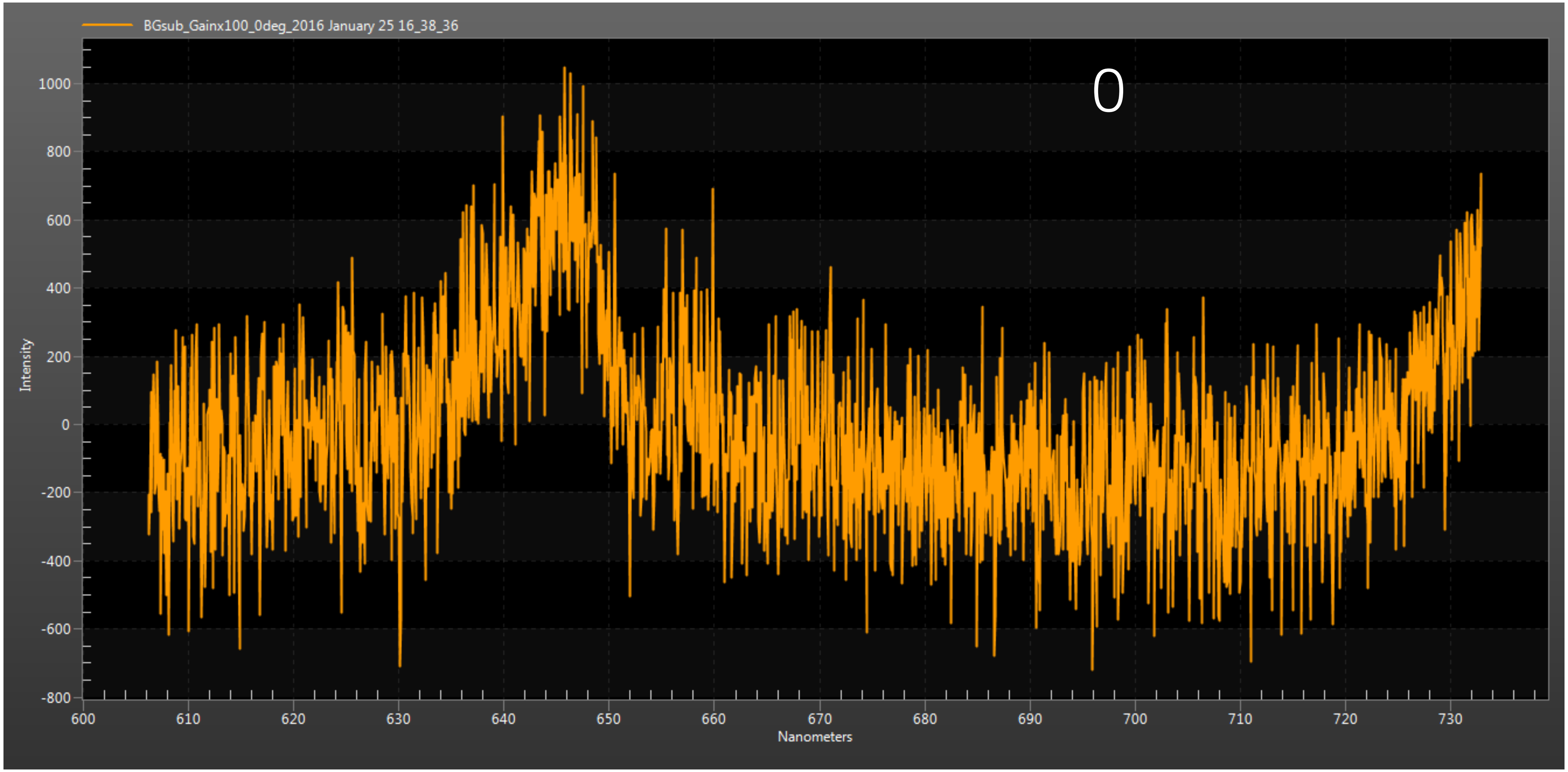
Pump polarization dependence of 645nm signal peak

Changing pump polarization angle:



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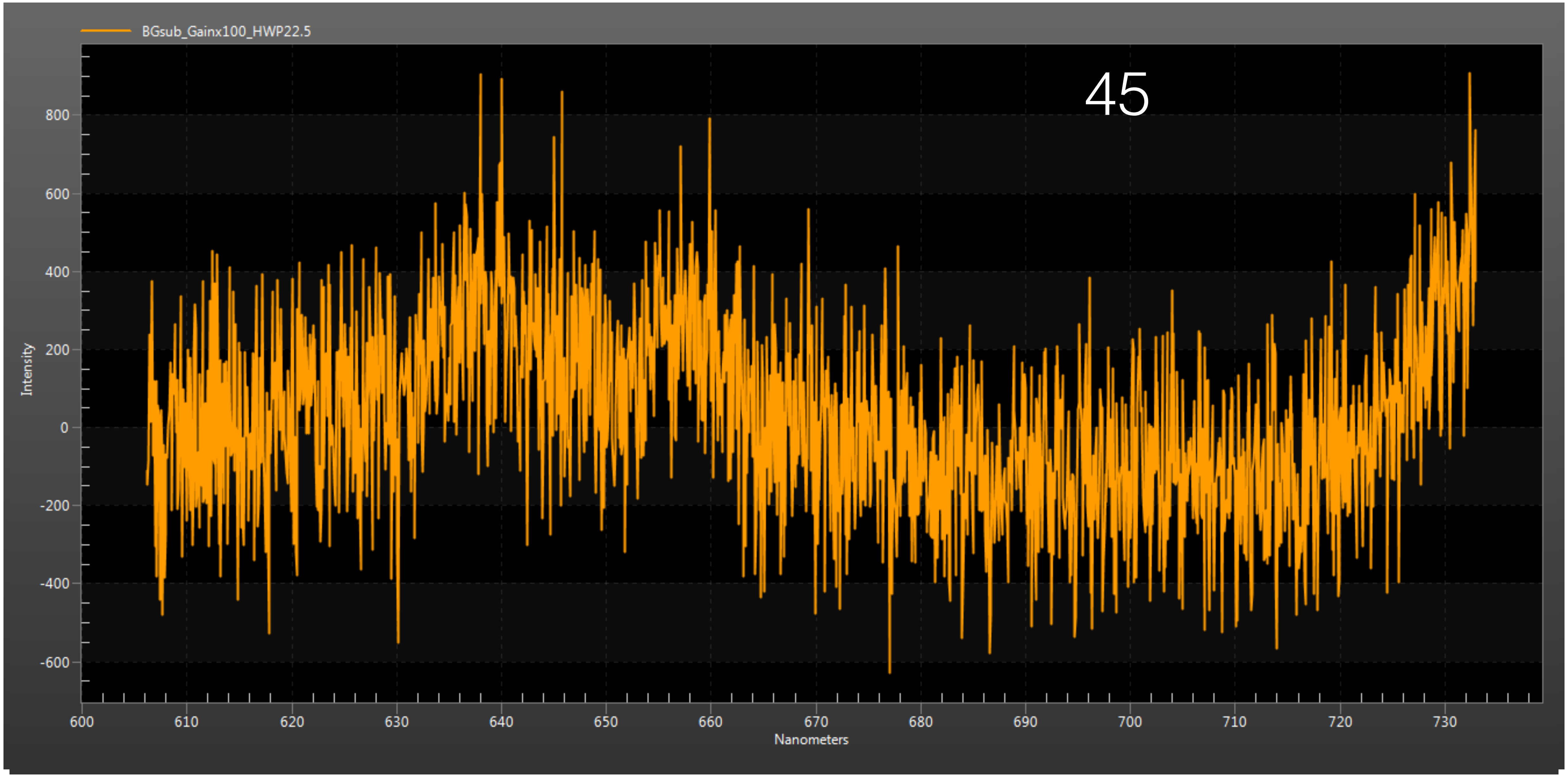

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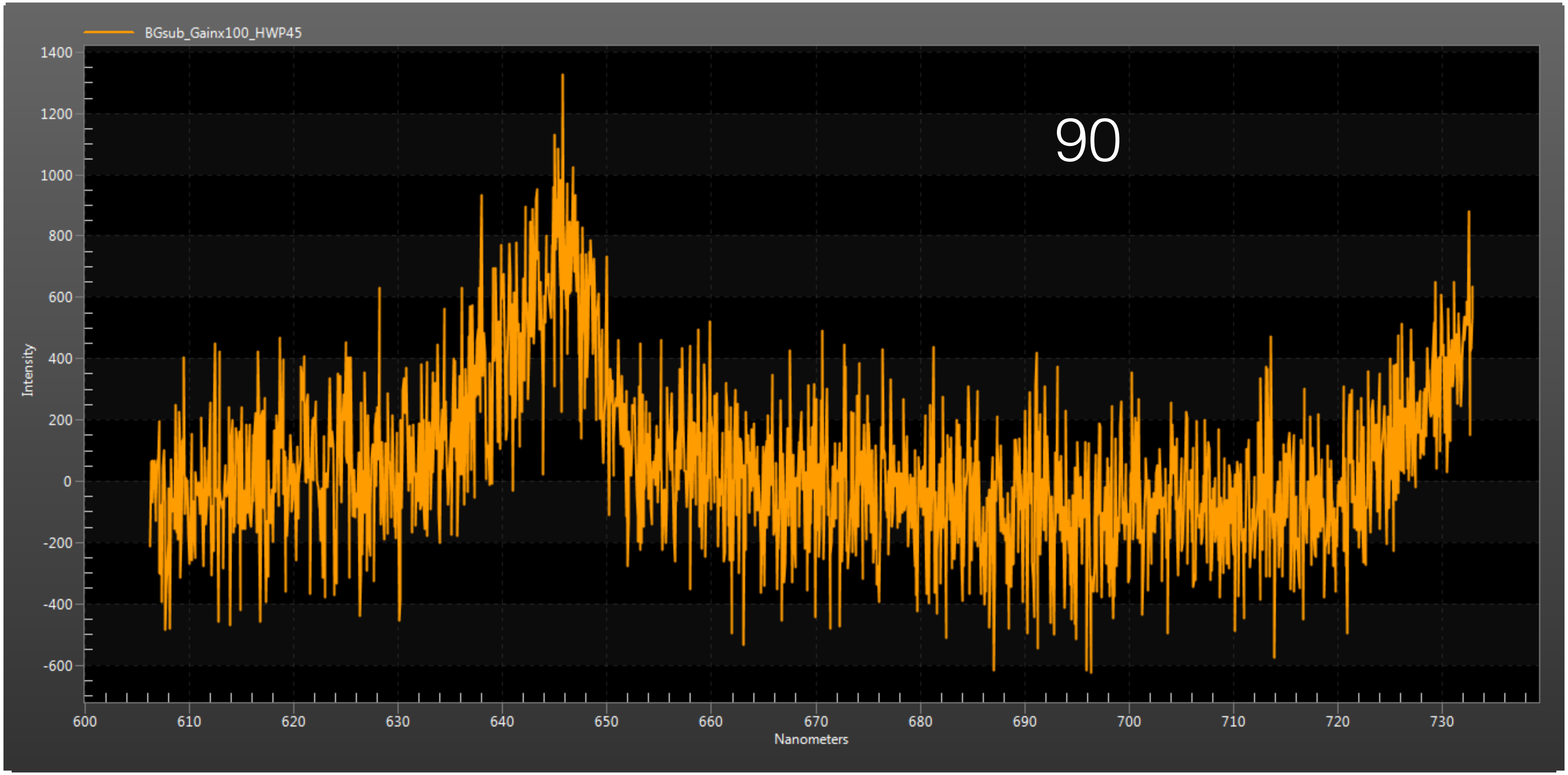

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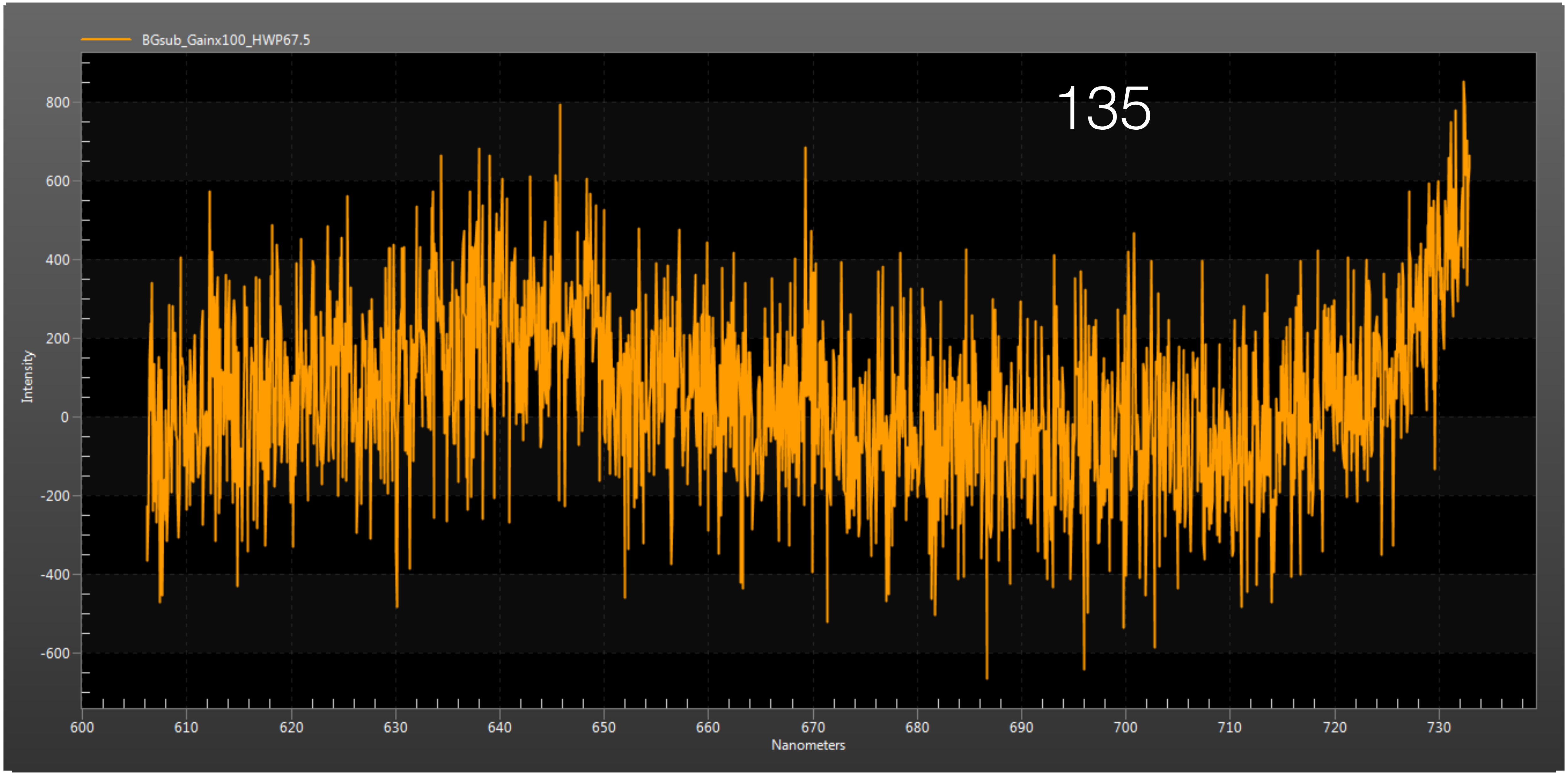

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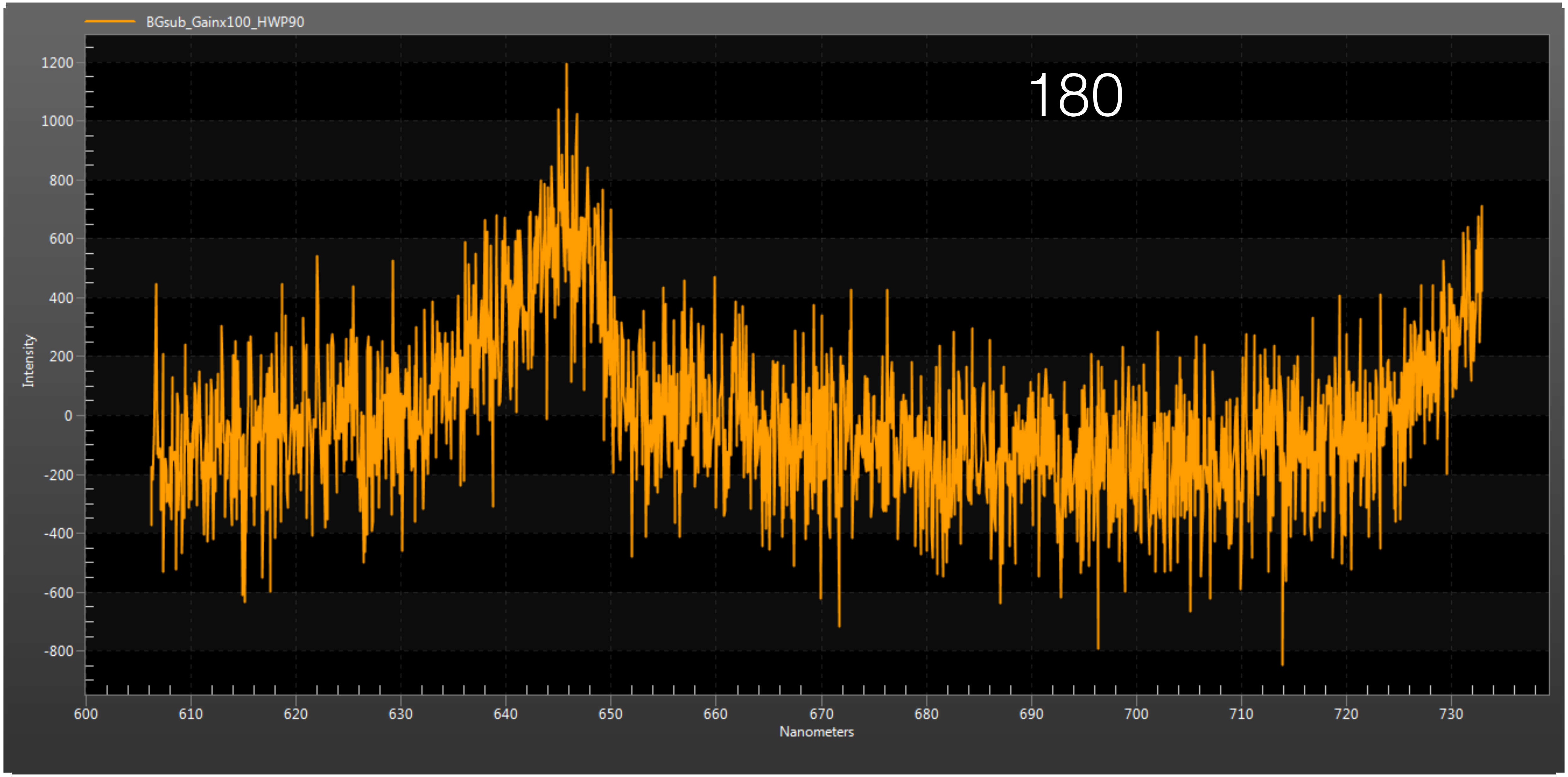

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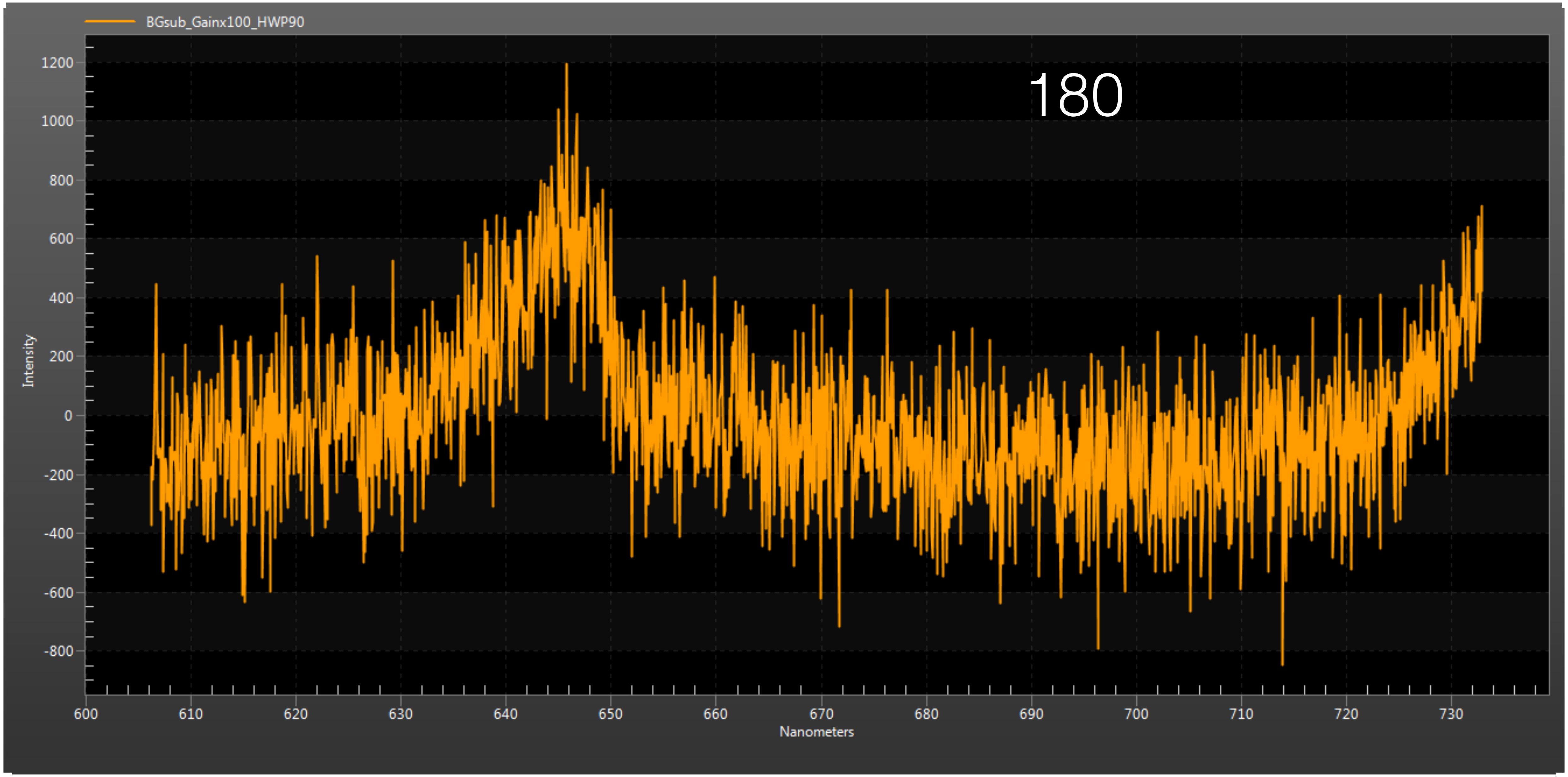
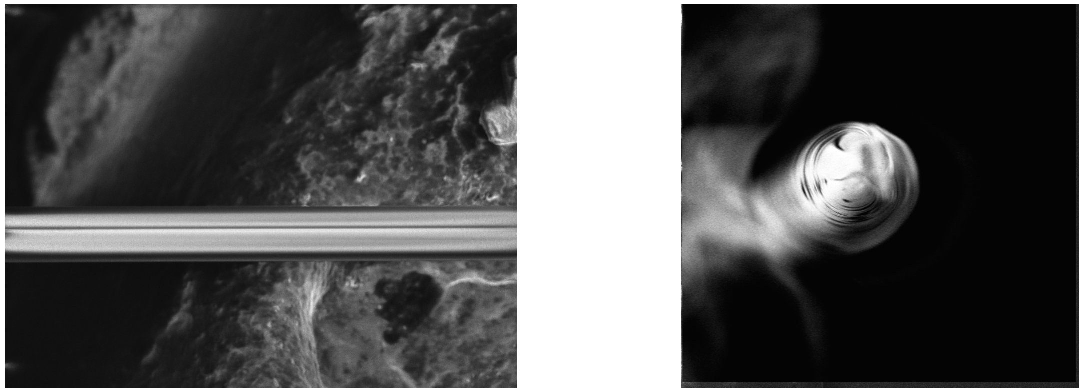


Pump polarization dependence: 90-degree periodicity
- consistent with orthogonally polarized pump photons

Summary

- Observed SFWM photon pair at 645nm and 1053nm in 1-micron-diameter microcoupler, from an xy —> xy phasematching process

- Goal: generation of polarization entangled photon pairs with fiber-based SFWM source



SEM images of 1um microcoupler, courtesy of Sebastian Schulz

Next steps:

- Solving phasematching with effective index simulation results to predict signal and idler wavelengths of SFWM photons

- Testing new 7 micron coupler for more SFWM peaks from different phasematching processes

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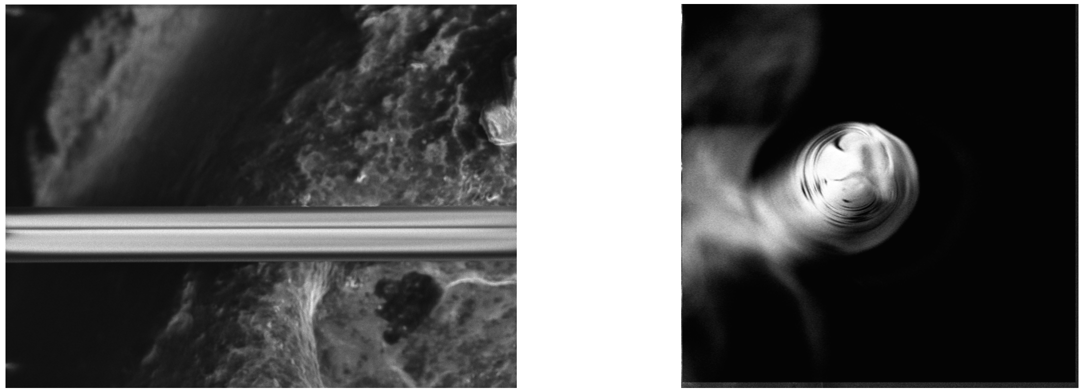

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Thank you!

References

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4. B. Smith, et al. *Opt. Express* **17**, 23589-23602 (2009).
5. G.Agrawal, Chapter 10 - Four-Wave Mixing, *Nonlinear Fiber Optics*, Fifth Edition 397-456 (2013).
6. C. Baker, M. Rochette, *Journal of Lightwave Technology*, **31**, 1, 171-176 (2013).

Phasematching processes allowed with xy —>xy for microcoupler

4 modes:
2 polarization (x,y)
2 spatial (even, odd)

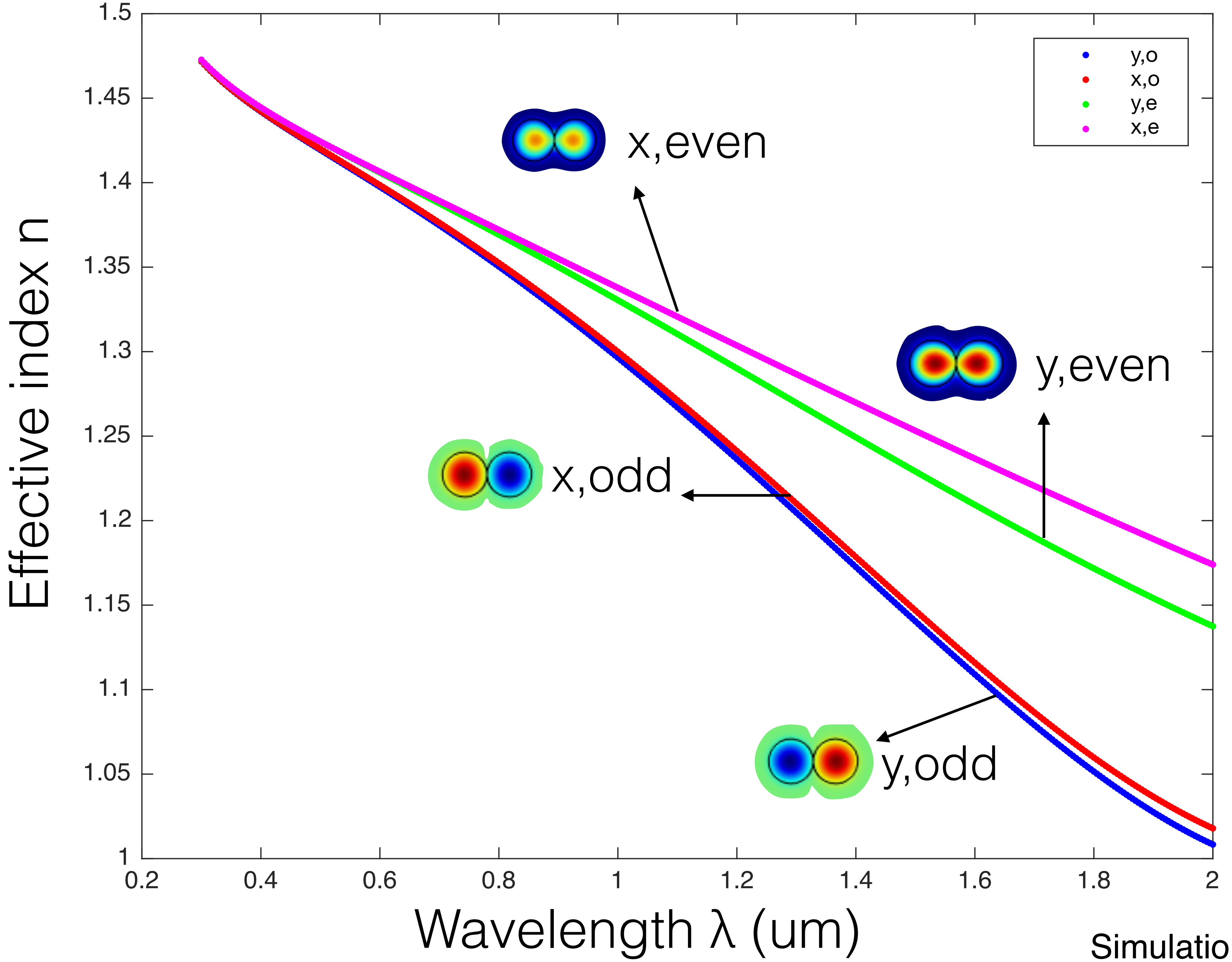
$$\boxed{\Delta k = k_{\mathrm{x,o}} + k_{\mathrm{y,o}} - k_{\mathrm{x,e}} - k_{\mathrm{y,e}} = 0}$$

- 7 allowed cases with orthogonally polarized pump photons
- Most likely when all photons have the same even/odd modes?

1	2	3	4
pump1	pump2	signal	idler
xe	yo	xo	ye
xe	yo	yo	xe
ye	xo	xo	ye
ye	xo	yo	xe
xe	ye	ye	xe
xo	yo	yo	xo
xo	yo	ye	xe

Simulation: effective index vs. wavelength

Effective index vs. wavelength for microcoupler *n(λ)*



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$$= 0$$

$$k_i = n_i\,\omega_i / c$$

Simulation results courtesy of Jefferson Flórez

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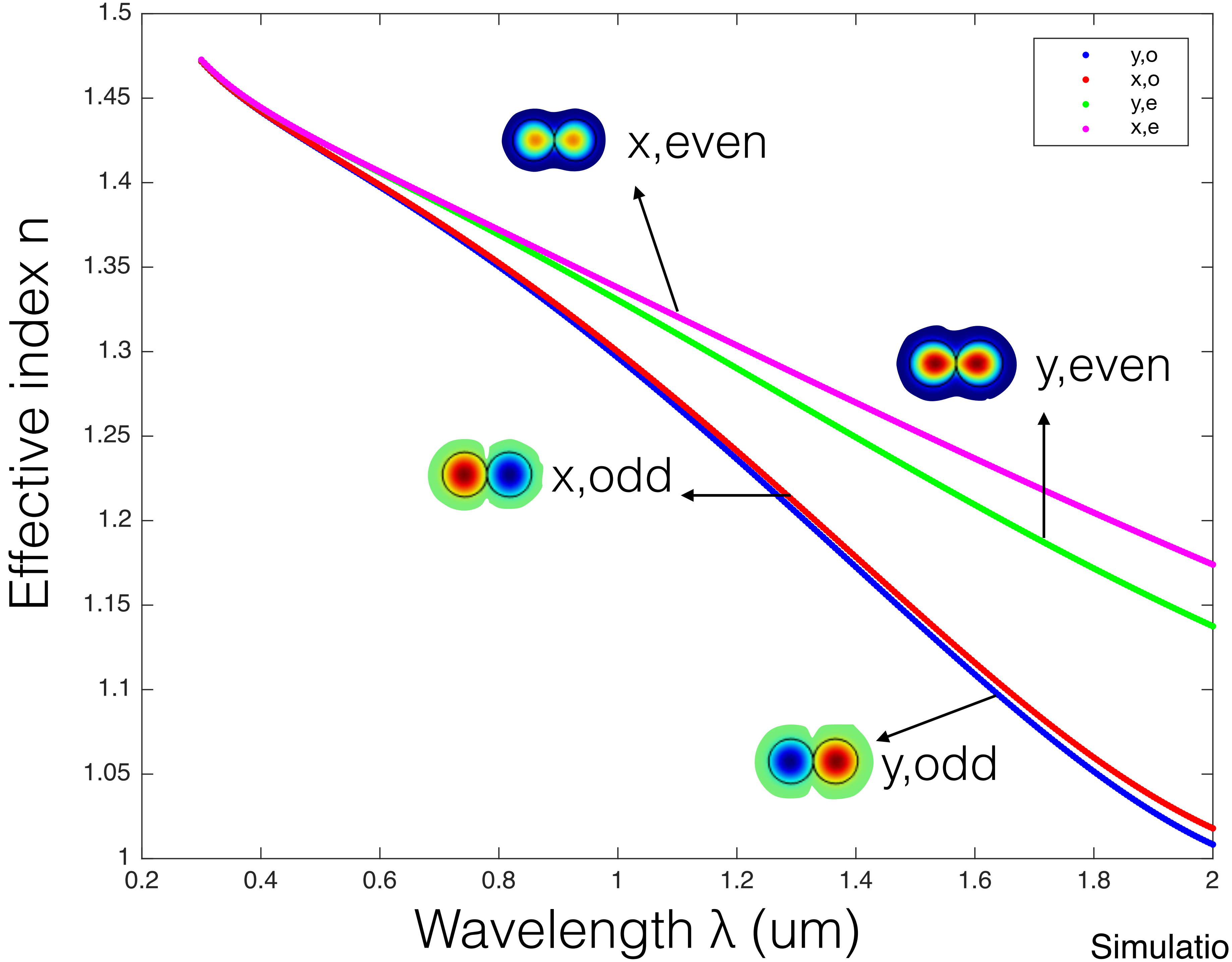

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Use n(λ) to find k and solve phasematching equation to predict the location of SFWM photon pairs

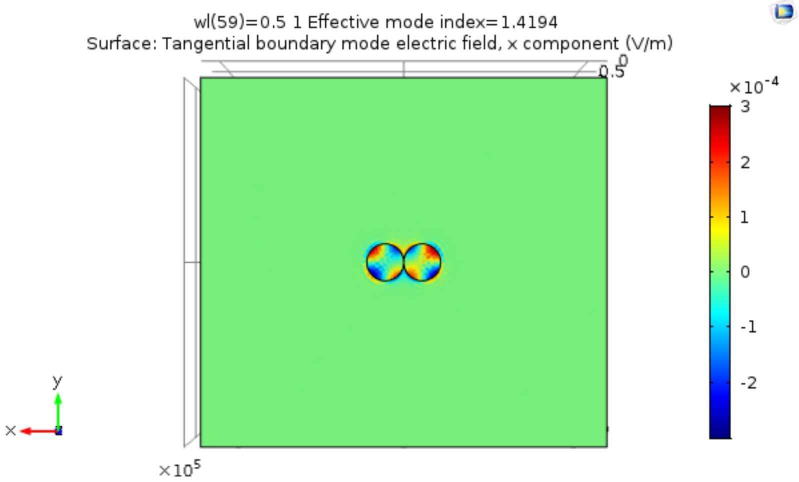
Simulation results courtesy of Jefferson Flórez

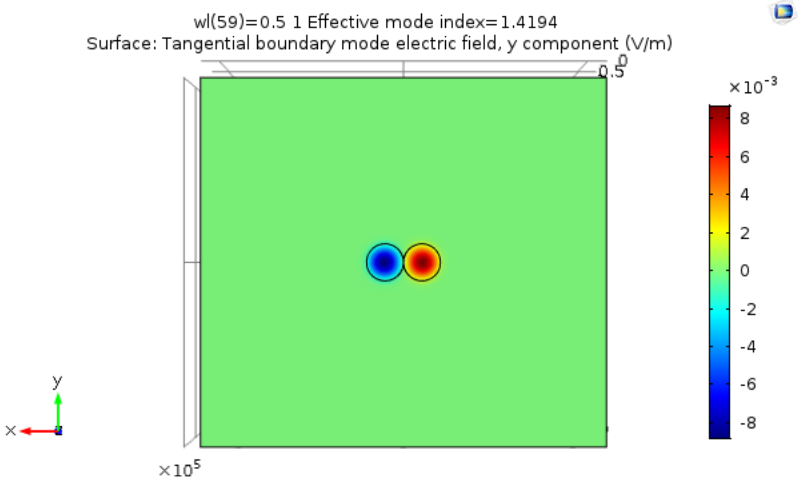
500 nm

E_x

E_y

1





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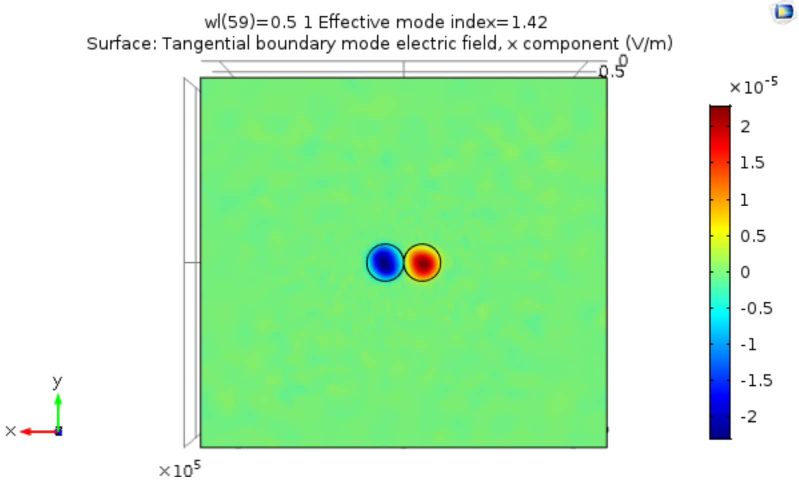

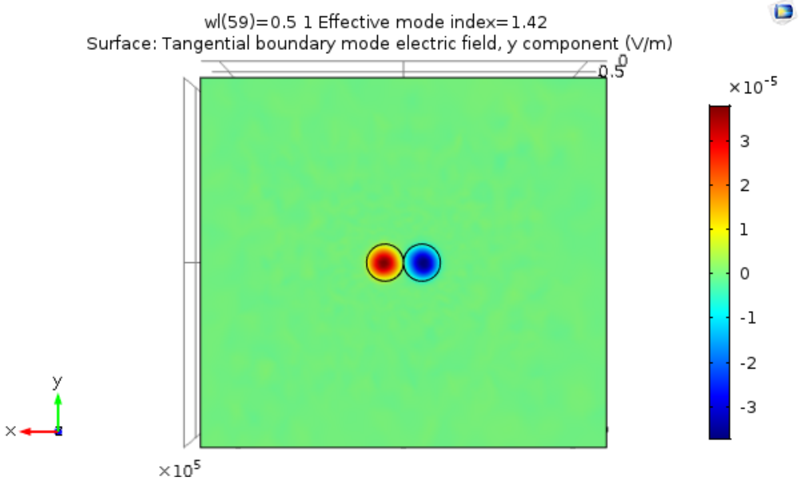

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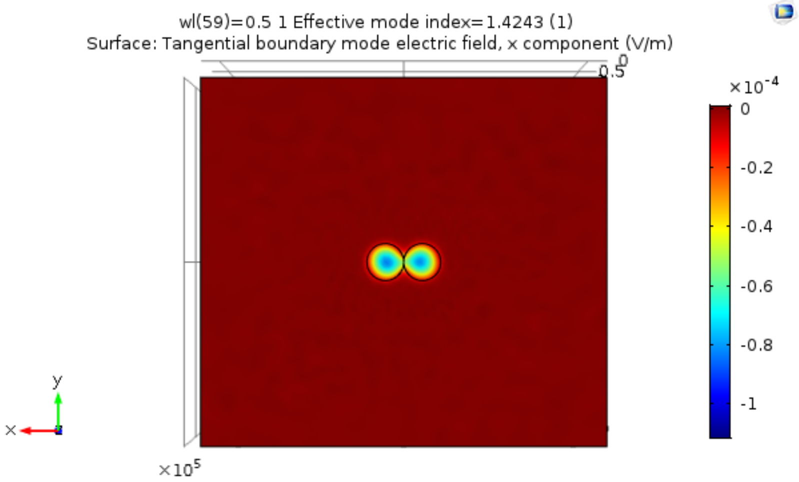

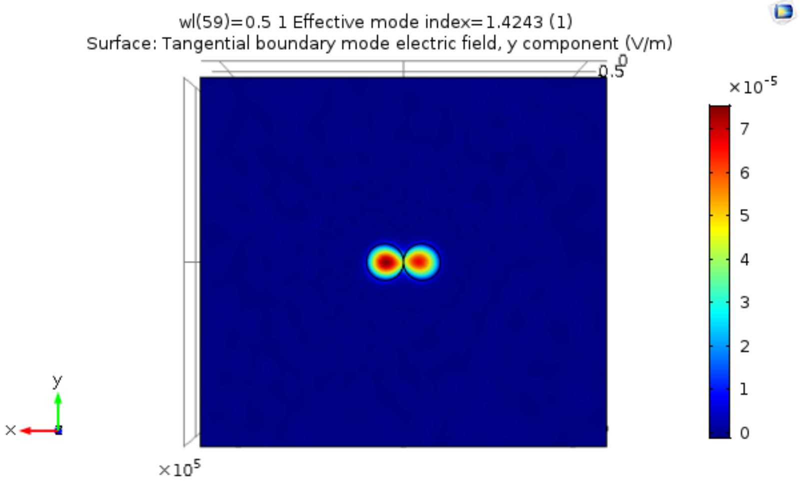

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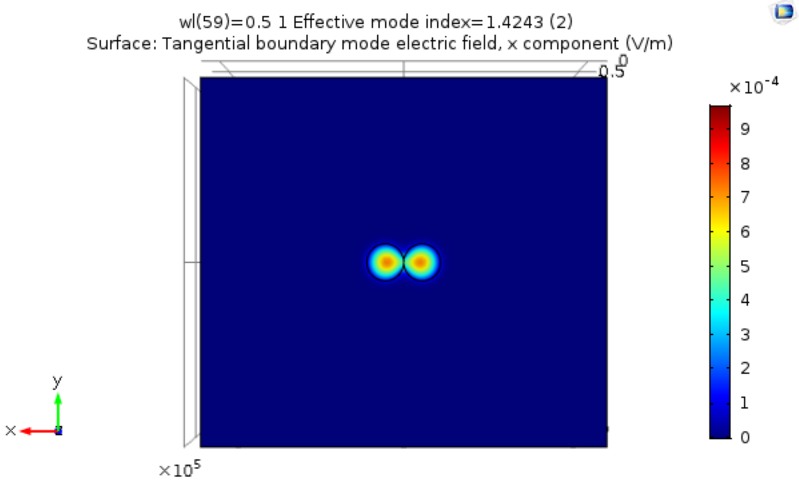
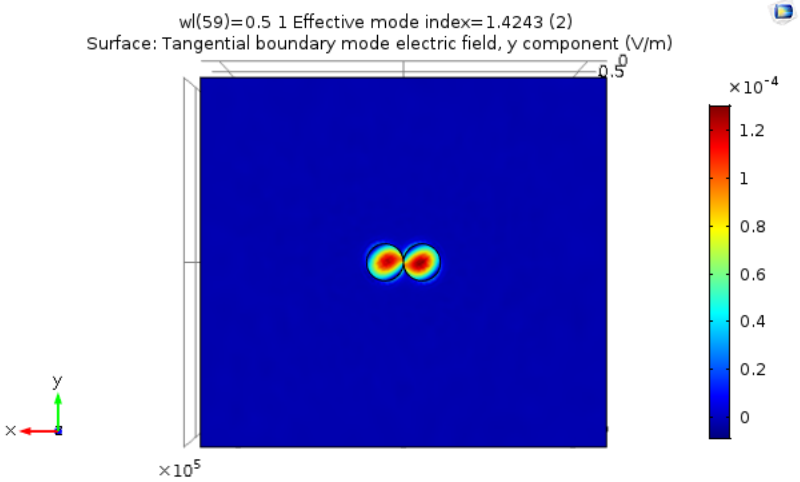


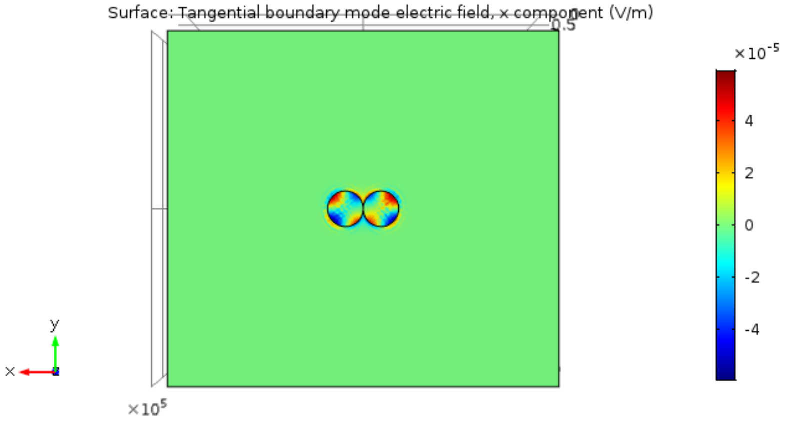


500 nm
New tolerance

E_x E_y

1

wl(59)=0.5 1 Effective mode index=1.4194
Surface: Tangential boundary mode electric field, x component (V/m)



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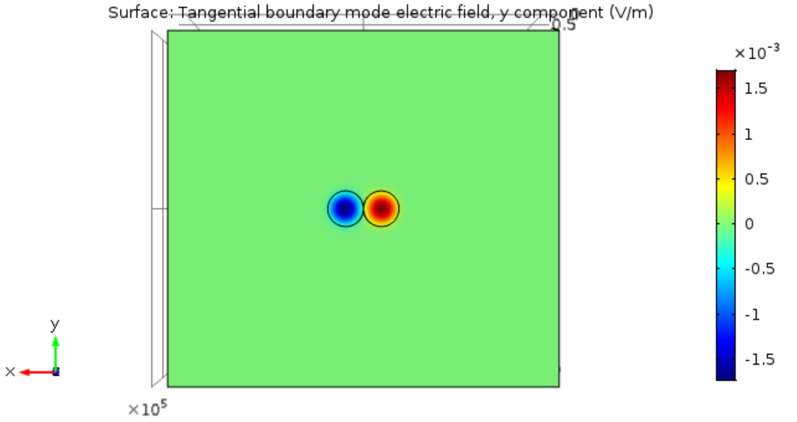
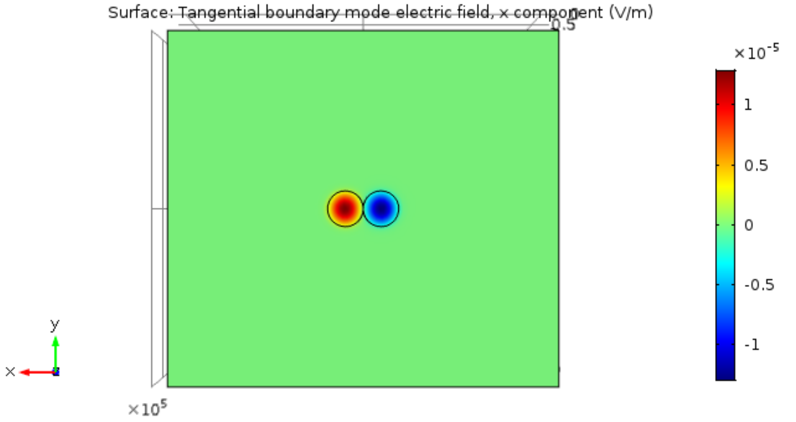
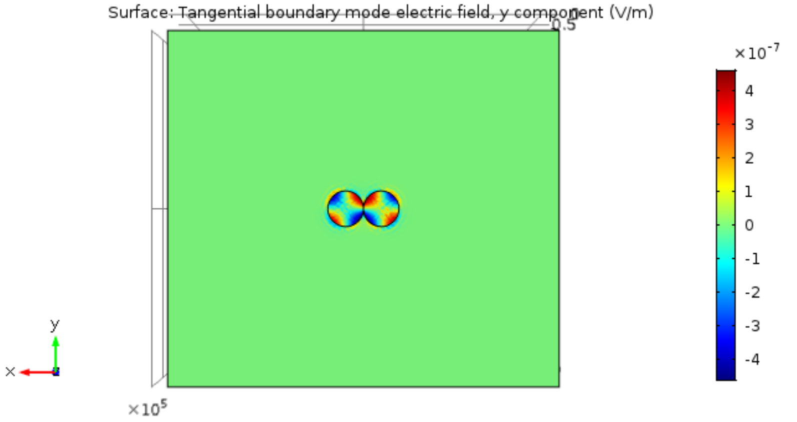


2

wl(59)=0.5 1 Effective mode index=1.42
Surface: Tangential boundary mode electric field, x component (V/m)

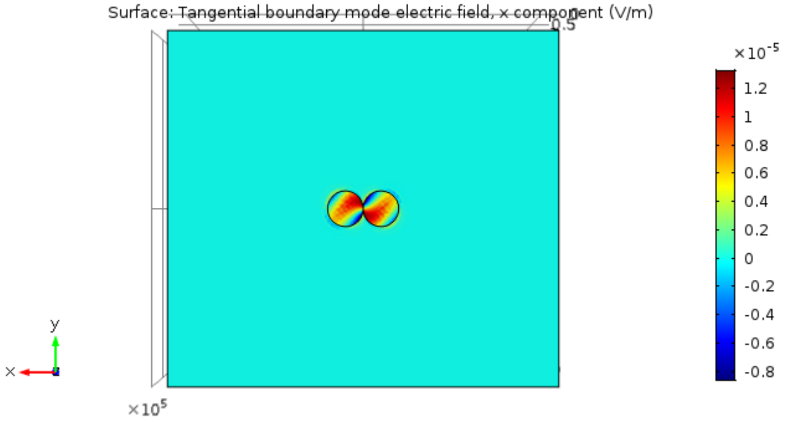


wl(59)=0.5 1 Effective mode index=1.42
Surface: Tangential boundary mode electric field, y component (V/m)

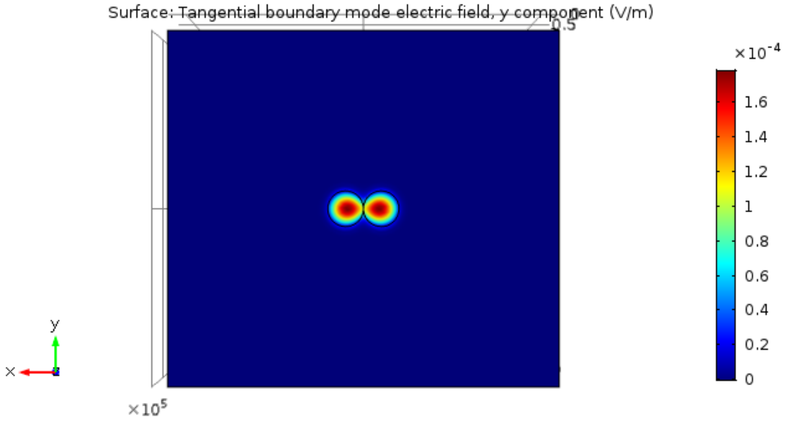


3

wl(59)=0.5 1 Effective mode index=1.4243 (1)
Surface: Tangential boundary mode electric field, x component (V/m)

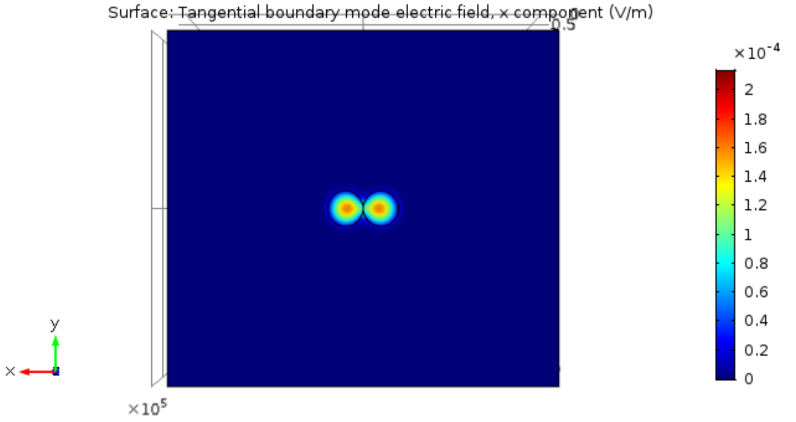


wl(59)=0.5 1 Effective mode index=1.4243 (1)
Surface: Tangential boundary mode electric field, y component (V/m)

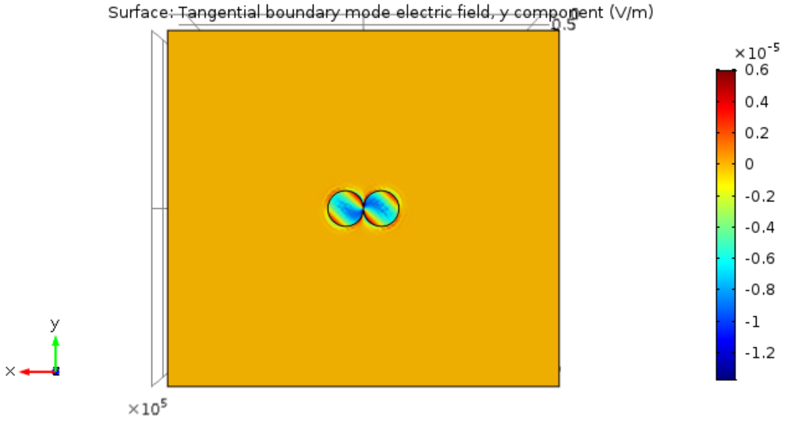


4

wl(59)=0.5 1 Effective mode index=1.4243 (2)
Surface: Tangential boundary mode electric field, x component (V/m)



wl(59)=0.5 1 Effective mode index=1.4243 (2)
Surface: Tangential boundary mode electric field, y component (V/m)

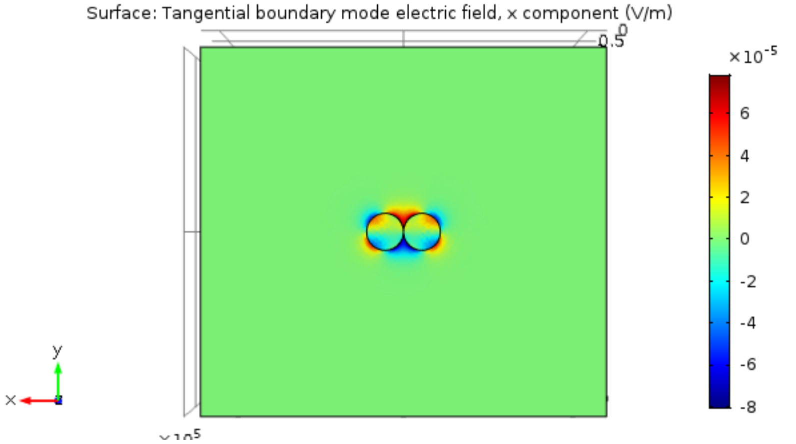


1000 nm

E_x E_y

1

wl(159)=1 1 Effective mode index=1.2964
Surface: Tangential boundary mode electric field, x component (V/m)



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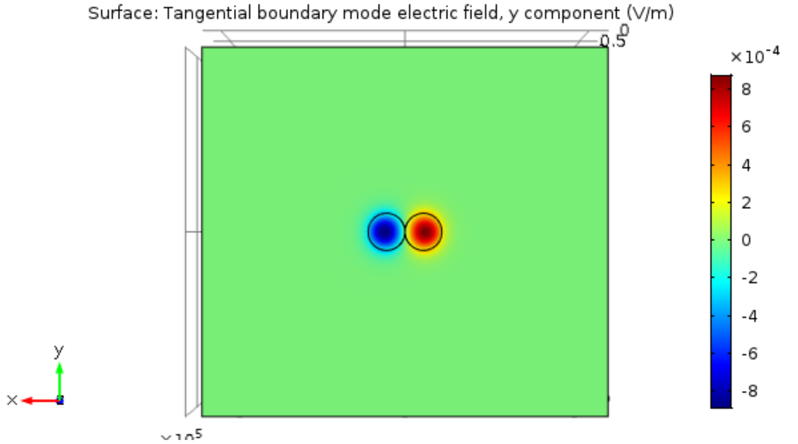
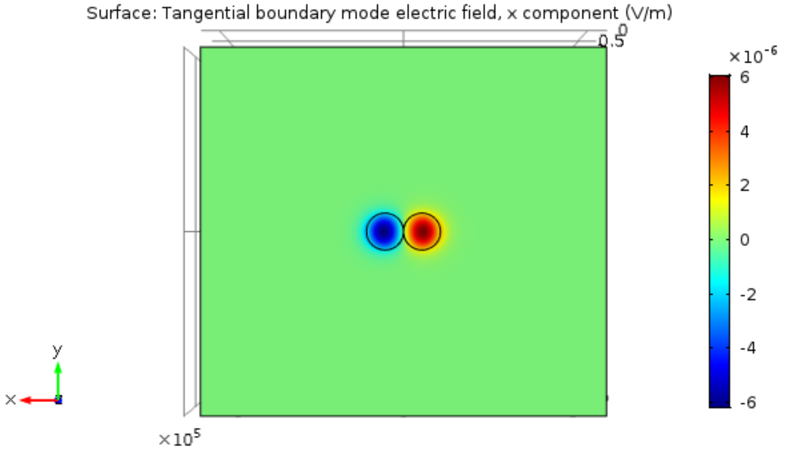


2

wl(159)=1 1 Effective mode index=1.2999
Surface: Tangential boundary mode electric field, x component (V/m)



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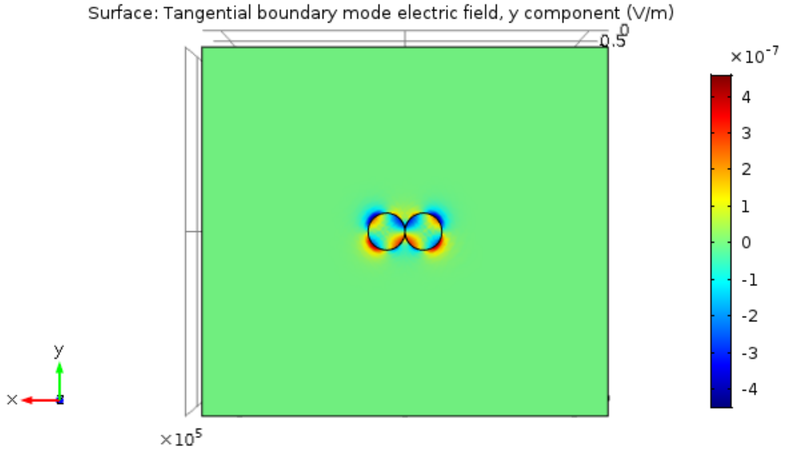
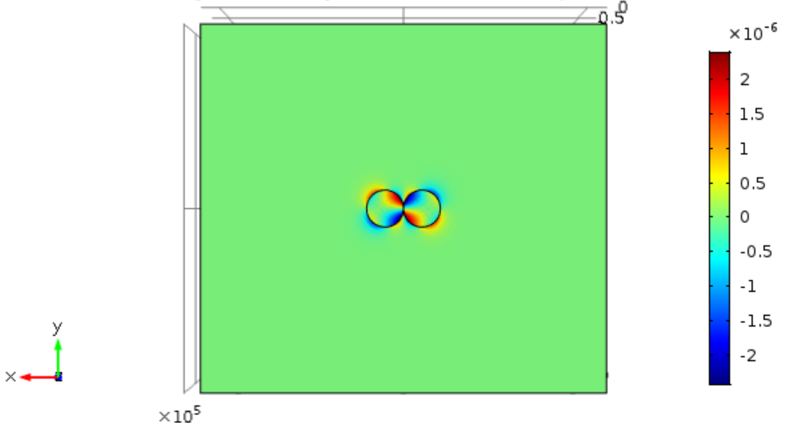


3

wl(159)=1 1 Effective mode index=1.3305
Surface: Tangential boundary mode electric field, x component (V/m)



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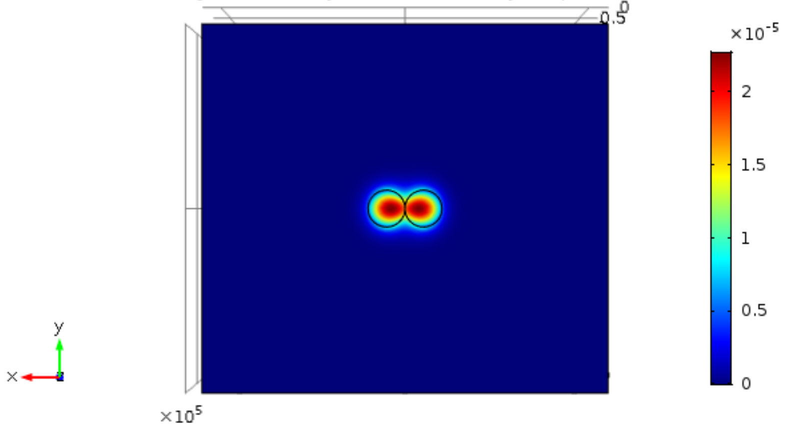
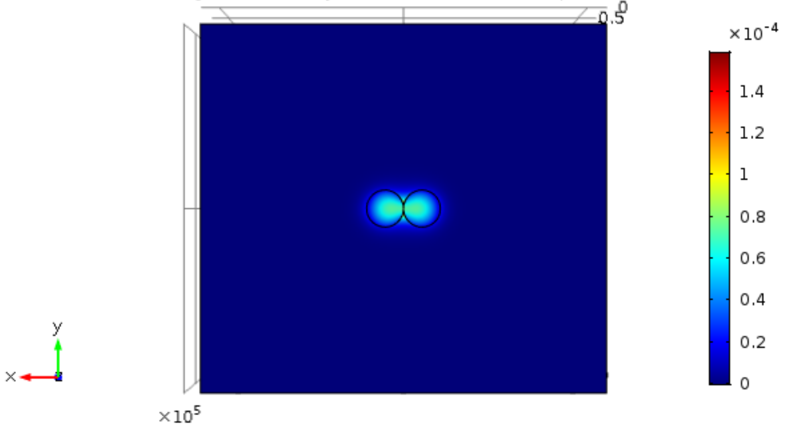
Surface: Tangential boundary mode electric field, y component (V/m)

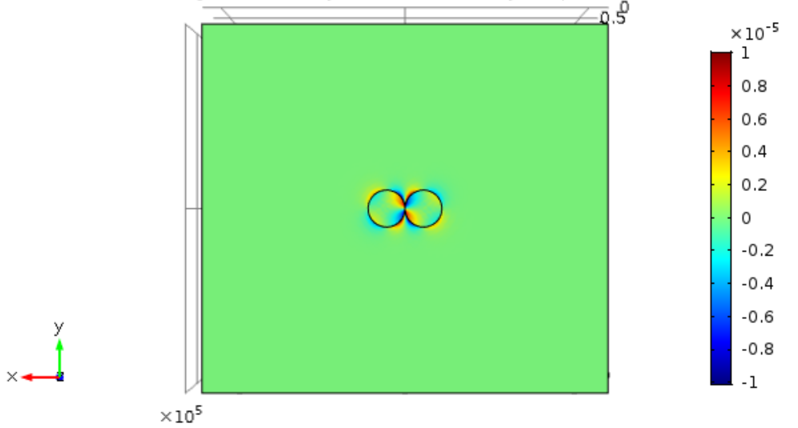


4

wl(159)=1 1 Effective mode index=1.3378
Surface: Tangential boundary mode electric field, x component (V/m)



wl(159)=1 1 Effective mode index=1.3378
Surface: Tangential boundary mode electric field, y component (V/m)

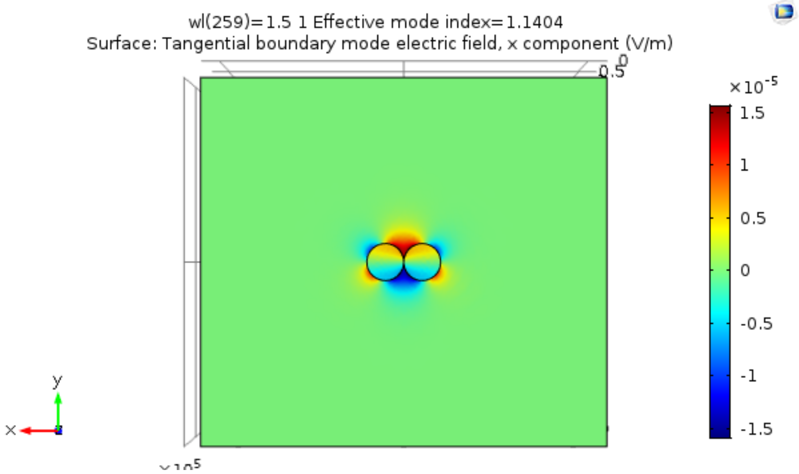


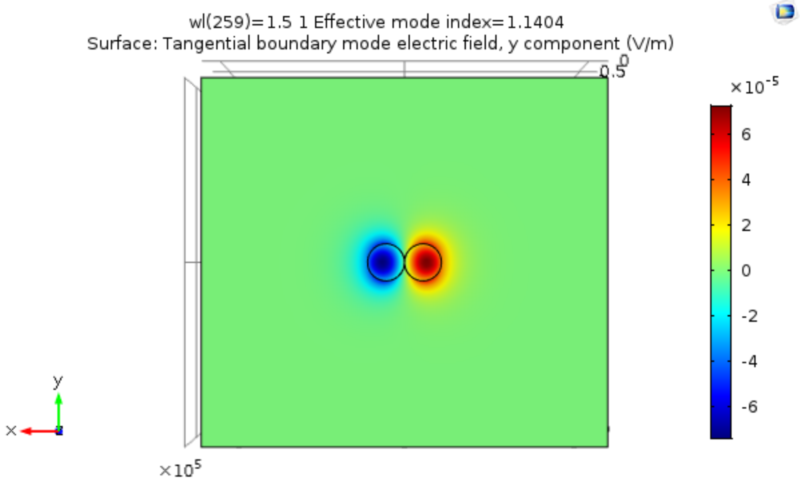
1500 nm

E_x

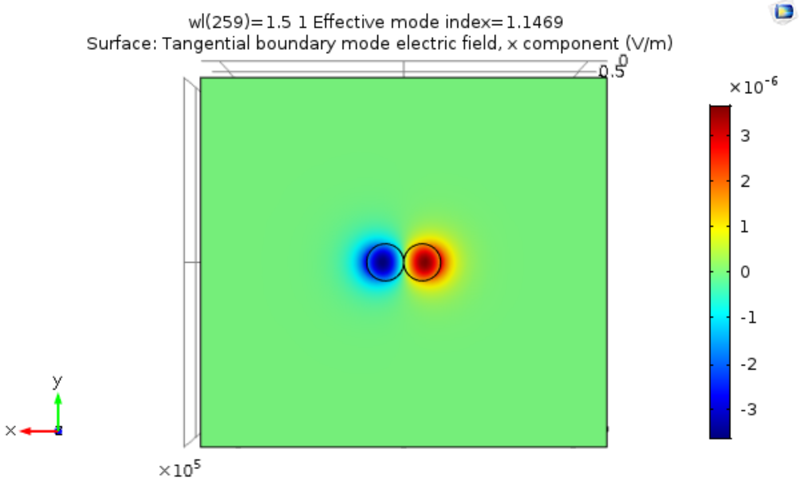
E_y

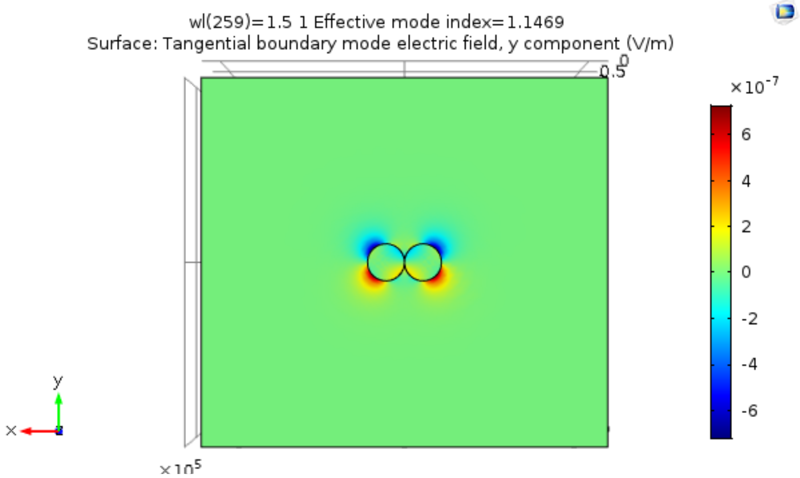
1



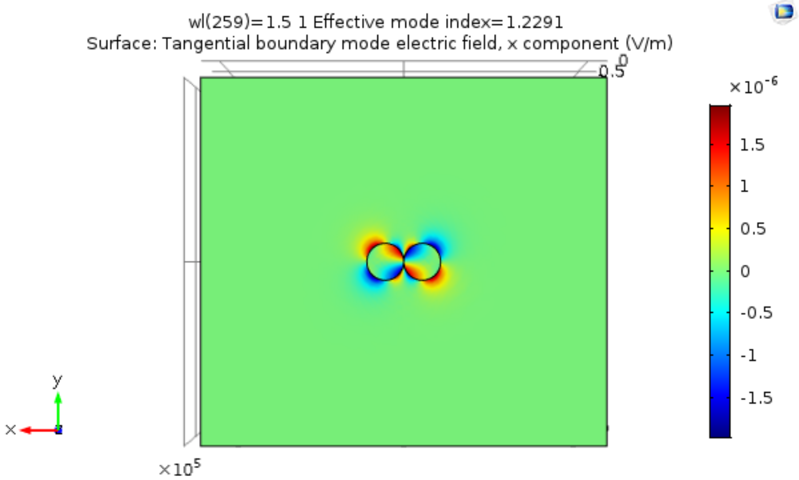


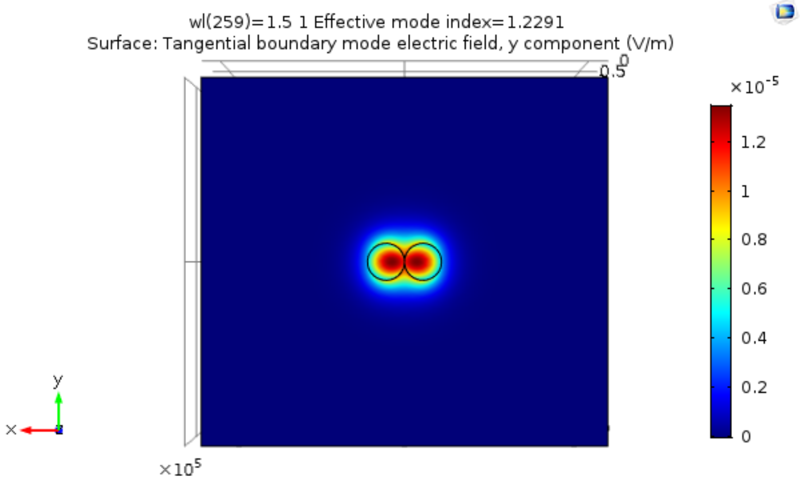
2



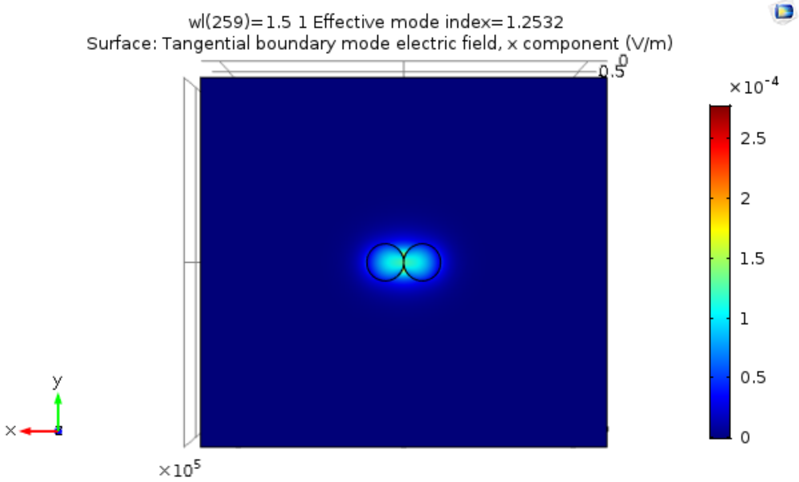


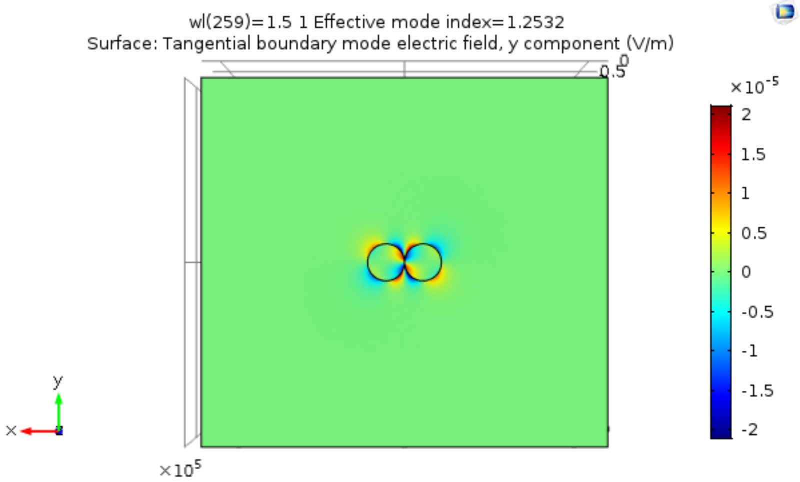
3





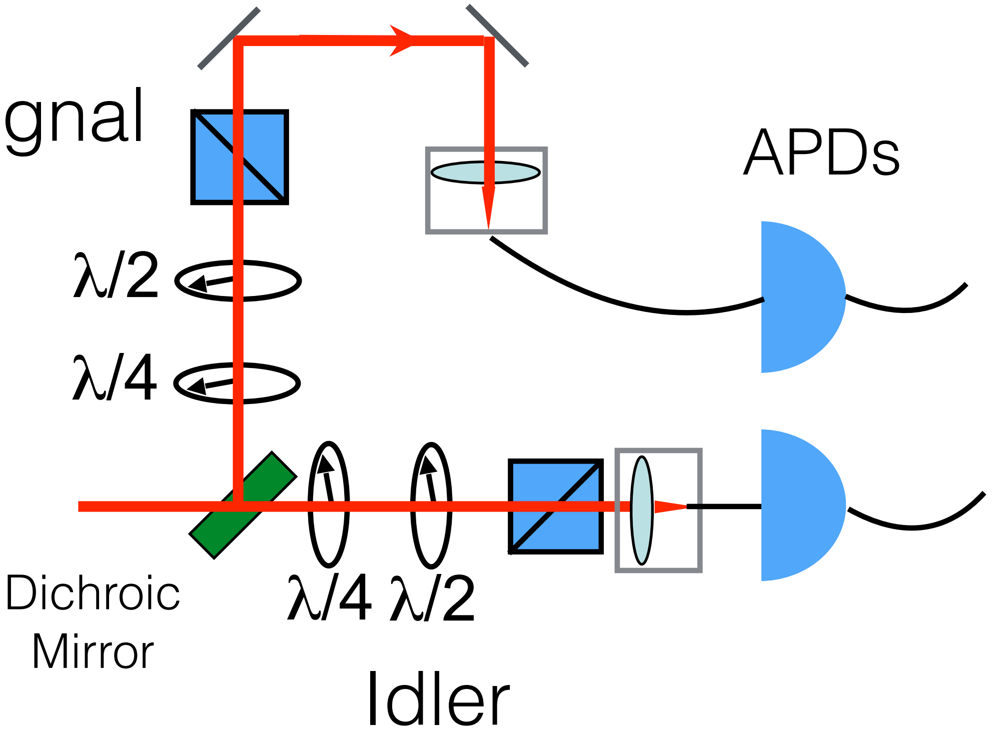
4





Polarization tomography analysis of SFWM photon pair

- Single-photon polarization tomography of signal and idler photon:



- Density matrices from APD data:

- Find Stokes vectors, normalize and extend to pure states; *how orthogonal are the two polarization states?*
  - find overlap between the two (if overlap = 0, orthogonal)

Polarization tomography analysis of SFWM photon pair

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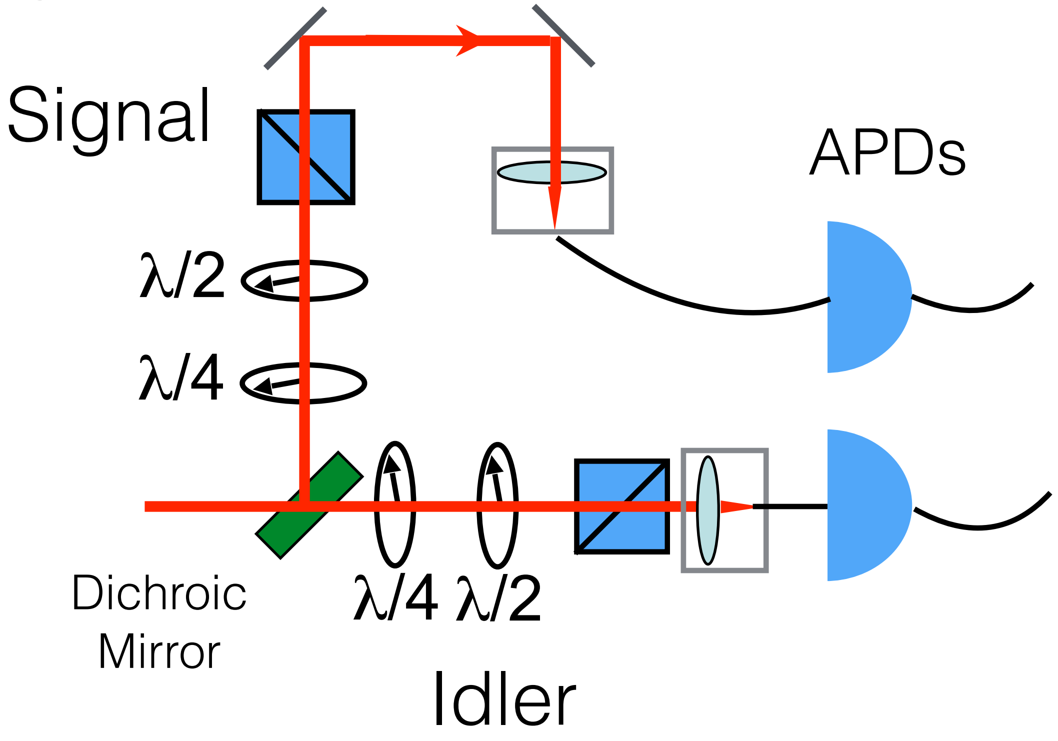

- Density matrices from APD data:

$$\rho_s = \begin{bmatrix} 0.862 & -0.163 - 0.109i \\ -0.163 + 0.109i & 0.138 \end{bmatrix}$$

$$\rho_i = \begin{bmatrix} 0.143 & -0.018 - 0.1765i \\ -0.018 + 0.1765i & 0.857 \end{bmatrix}$$

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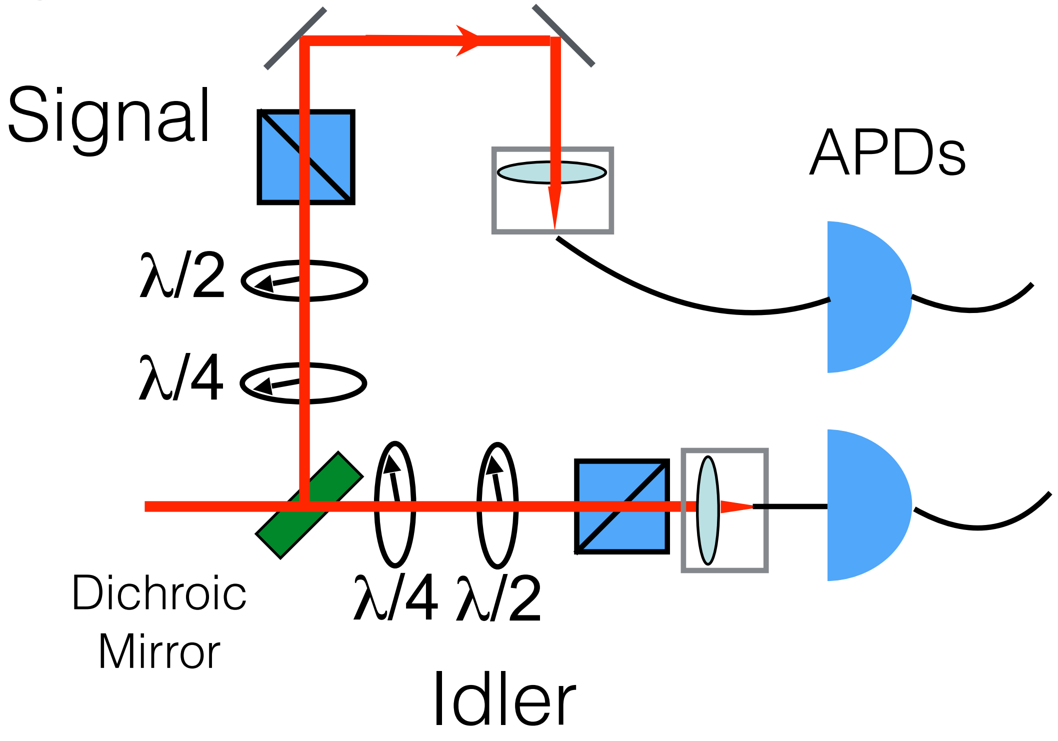

- Find Stokes vectors, normalize and extend to pure states; *how orthogonal are the two polarization states?*
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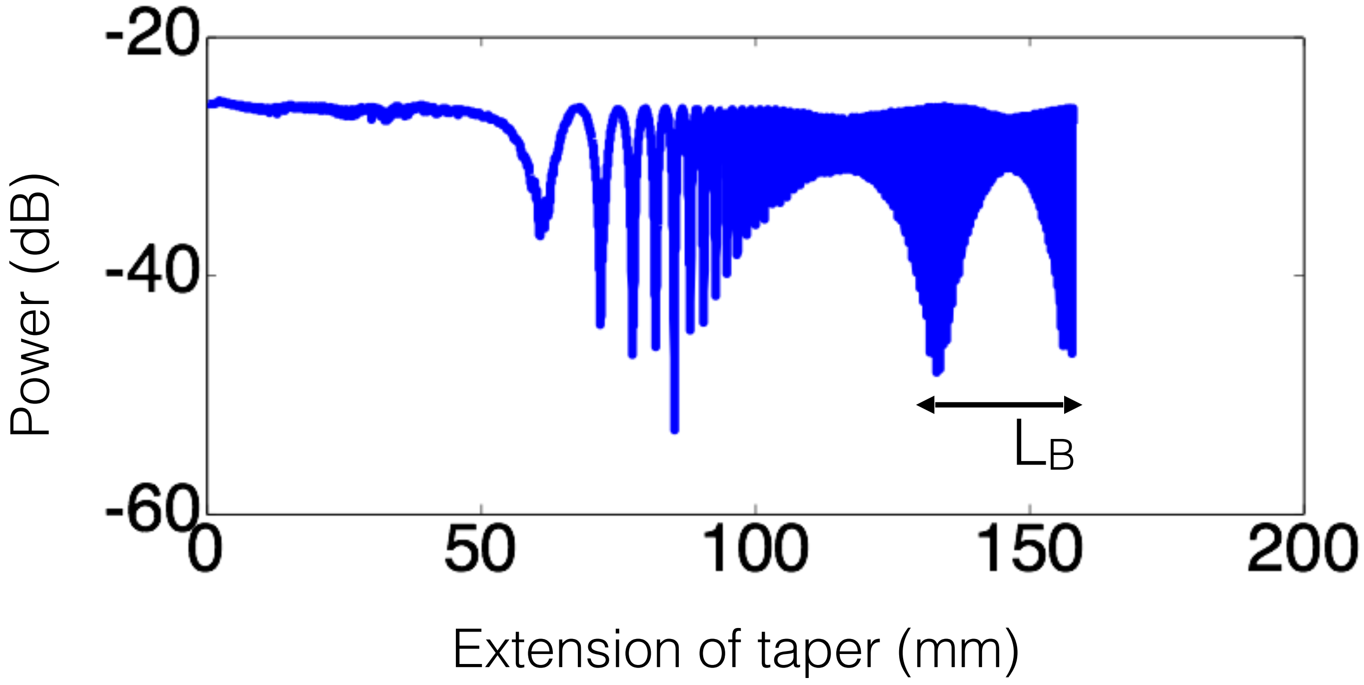
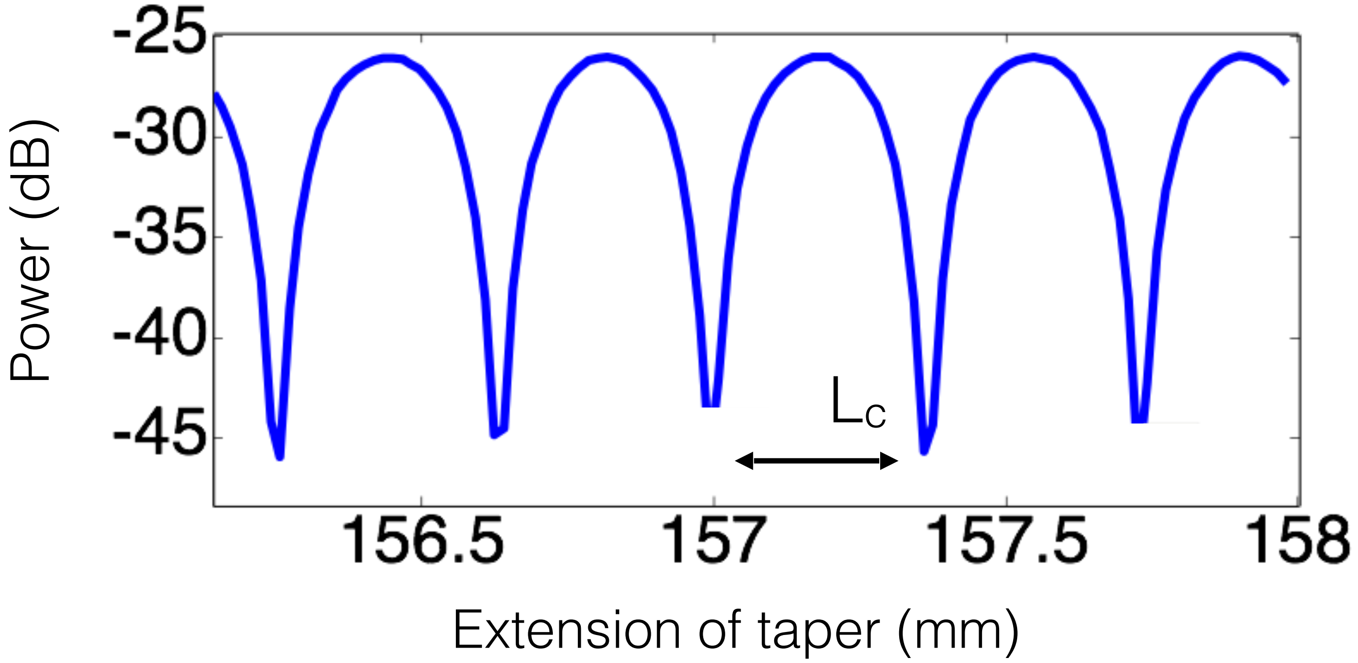
Overlap = 0.1738

New microcoupler - 7 micron in diameter



- fabrication data: approximate coupling length=0.36mm (for even/odd modes) and beat length~=24mm (for birefringent modes)



- prediction: expect to see fringes from even and odd spatial modes on spectrometer (5nm spacing);
- birefringent mode splittings 50nm apart

Plots courtesy of Chams Baker