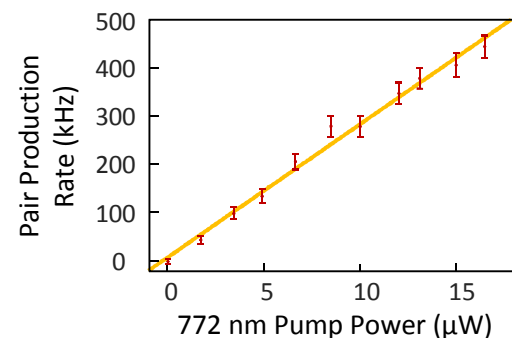
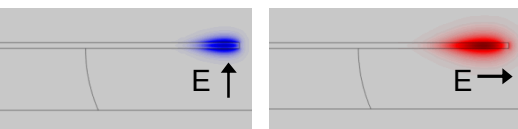
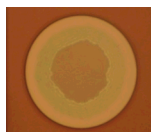
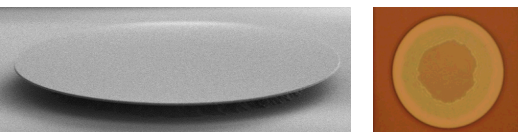




Entangled Photon Generation in Lithium Niobate Microdisk Resonators Through Spontaneous Parametric Down Conversion

Ian W. Frank, Jeremy Moore, J.K. Douglas, Ryan Camacho, and Matt Eichenfield

Sandia National Laboratories, Albuquerque, NM



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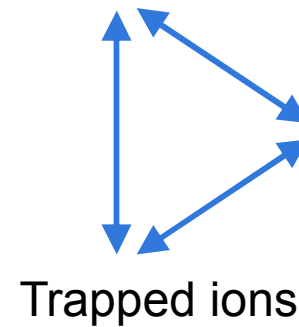
Outline

- Motivation
- Lithium niobate
 - LiNbO_3 on Insulator (LNOI)
- Geometric phase matching in LNOI microdisks
- Fabrication/microdisk characterization
- Second harmonic generation (SHG) in LNOI microdisks
- Spontaneous parametric down conversion (SPDC)
 - Conversion efficiency/pair production rate
 - Coincidence spectra
- Conclusion

Motivation

- Low power, chip-scale frequency conversion
 - Similar system for second harmonic generation, etc.
 - Linking different quantum systems
- Entangled photon generation

Neutral cold atoms

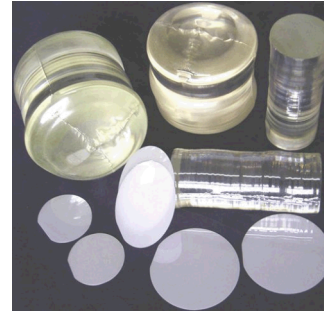


Diamond defects

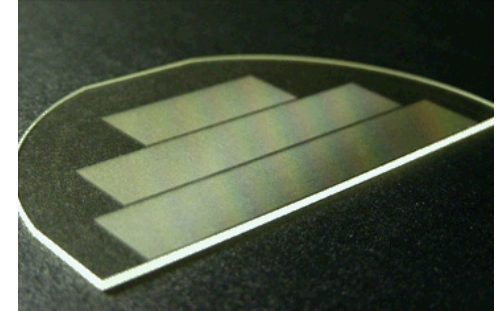
Lithium Niobate (LiNbO_3)

- Many available nonlinear materials
 - BBO
 - KTP
 - LiTaO_3
 - AlN
 - GaAs
- LiNbO_3
 - Large nonlinear optical coefficient
 - $d_{33} = 31.5 \text{ pm/V}$
 - $d_{31} = 4.5 \text{ pm/V}$
 - Wide transparency window
 - $350 \text{ nm} - 5 \mu\text{m}$

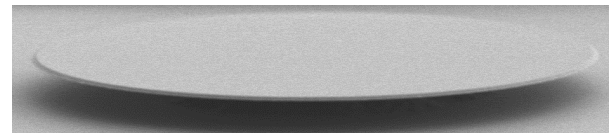
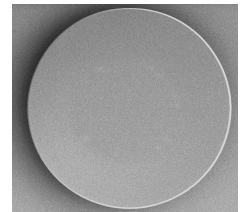
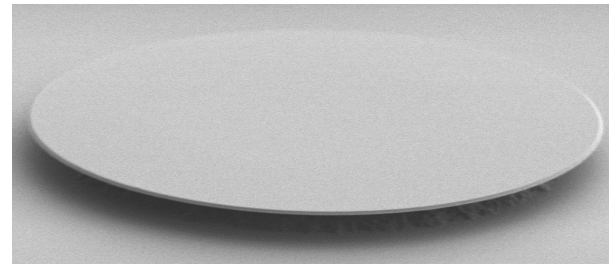
Bulk LiNbO_3^*



PPLN wafer**



LiNbO_3 on Insulator (LNOI) Microdisks

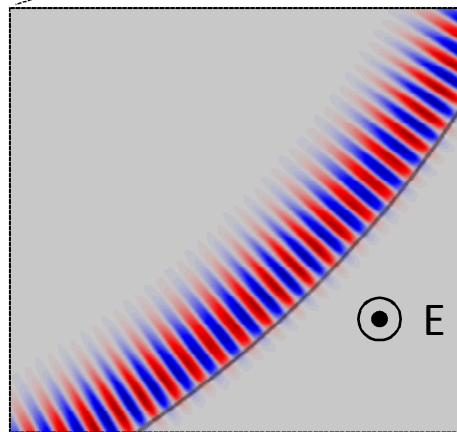
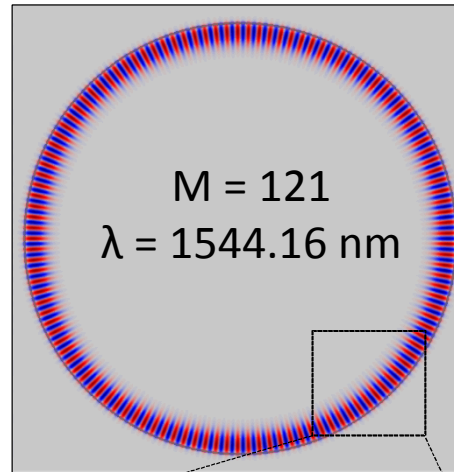
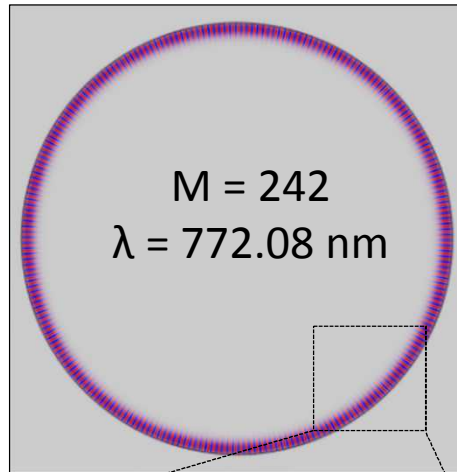


*DFNano

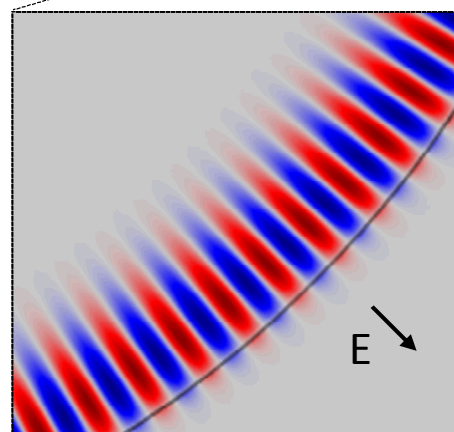
**Deltronic Crystal Industries

Geometric Phase Matching

Phase matching condition



Pump



Signal (idler)

Momentum conservation:

$$M_{pump} = 2 \times M_{signal}$$

$$\Delta M = M_{pump} - (2 \times M_{signal}) = 0$$

Energy conservation:

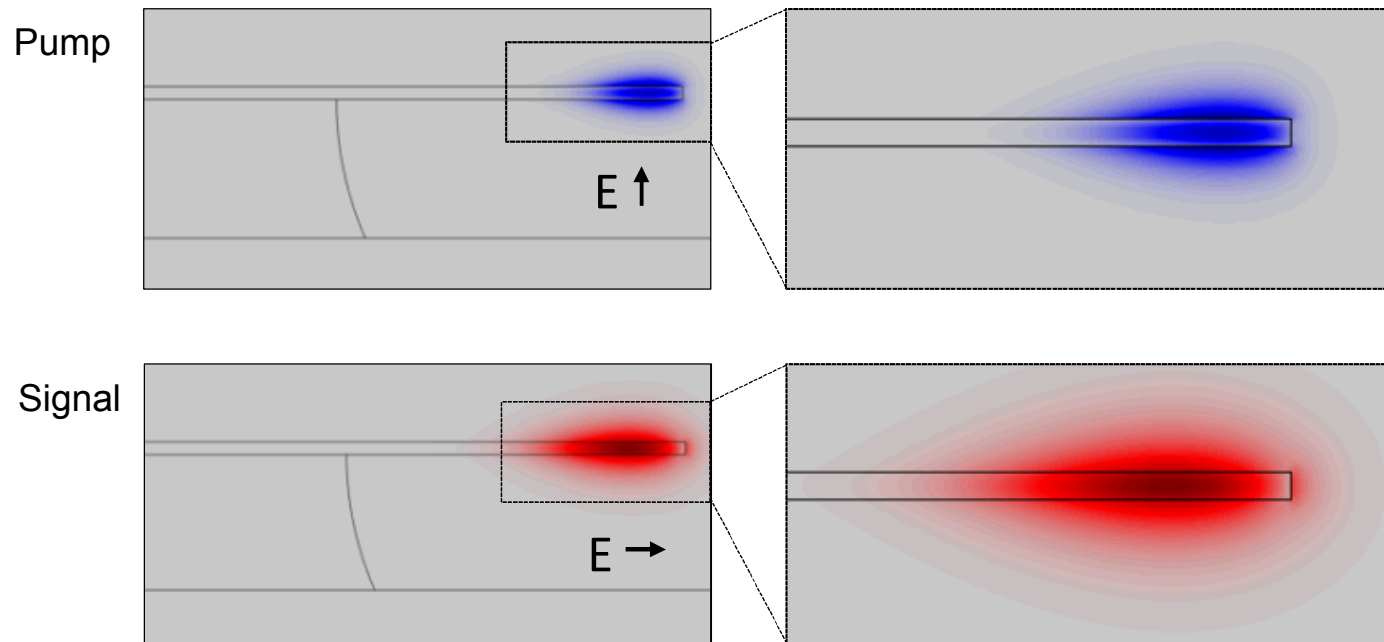
$$\lambda_{pump} = \frac{1}{2} \lambda_{signal}$$

$$f_{pump} = 2 \times f_{signal}$$

$$\Delta f = f_{pump} - (2 \times f_{signal}) = 0$$

Geometric Phase Matching

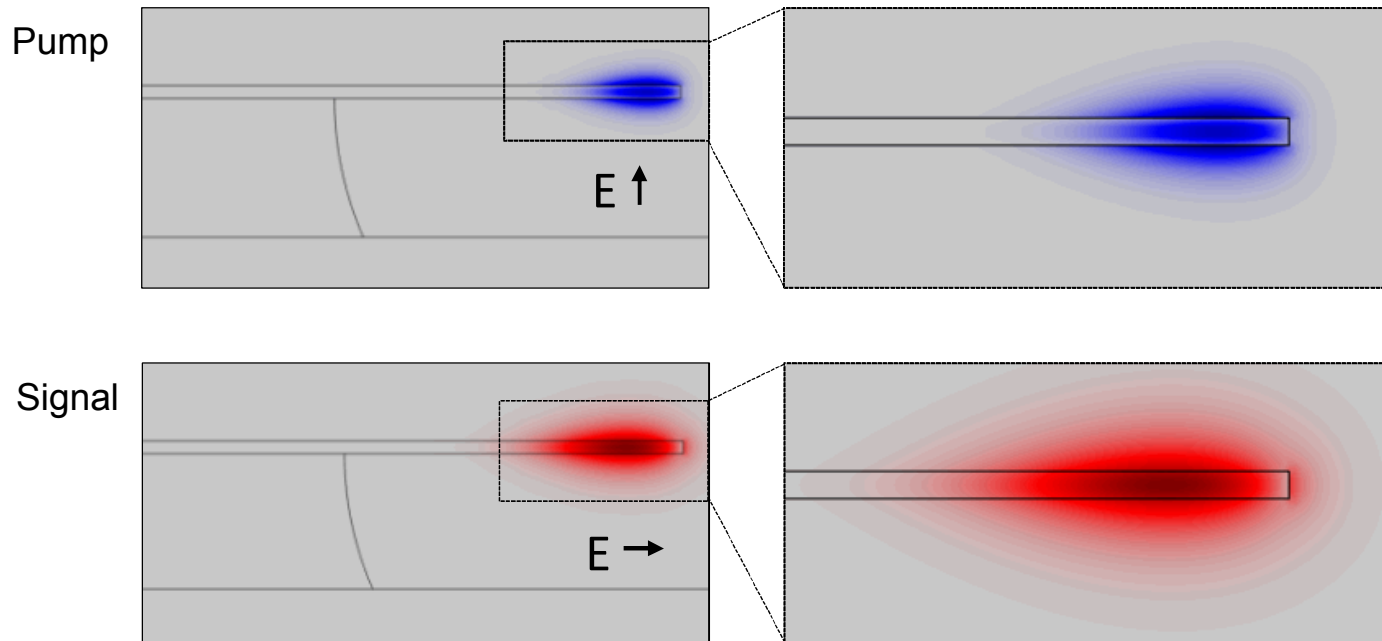
Mechanism



- Dispersion is a stronger function of aspect ratio for vertically polarized (TM) modes.

Geometric Phase Matching

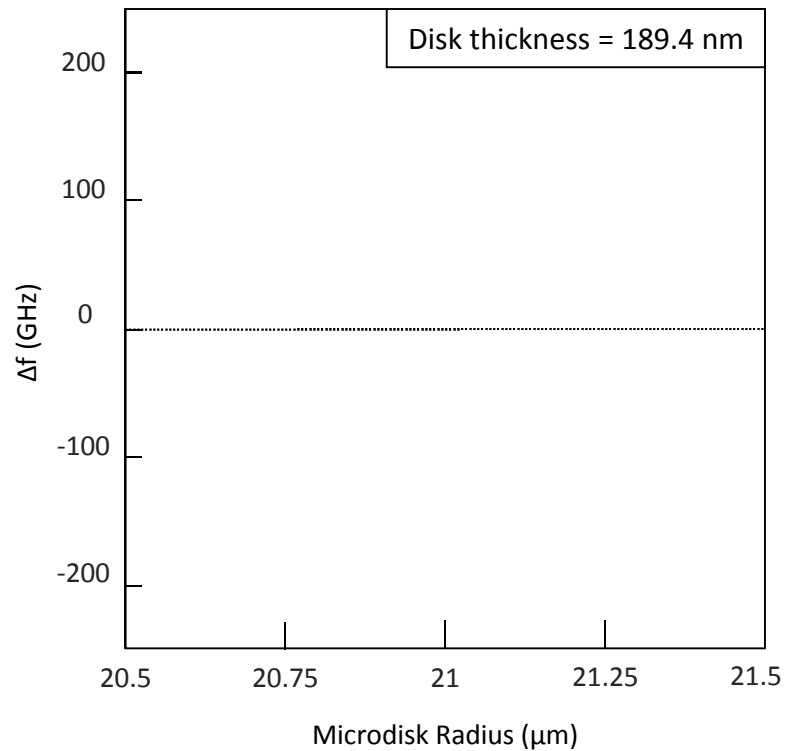
Mechanism



- Dispersion is a stronger function of aspect ratio for vertically polarized (TM) modes.
- For a given disk thickness and M_{pump}/M_{signal} pair, change the disk radius to achieve phase matching

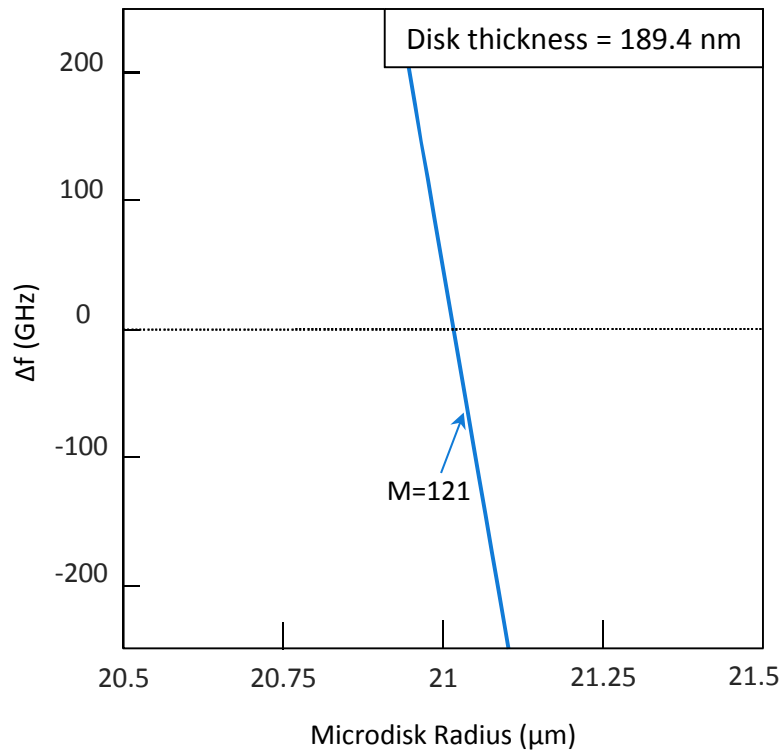
Geometric Phase Matching

Phase matching algorithm



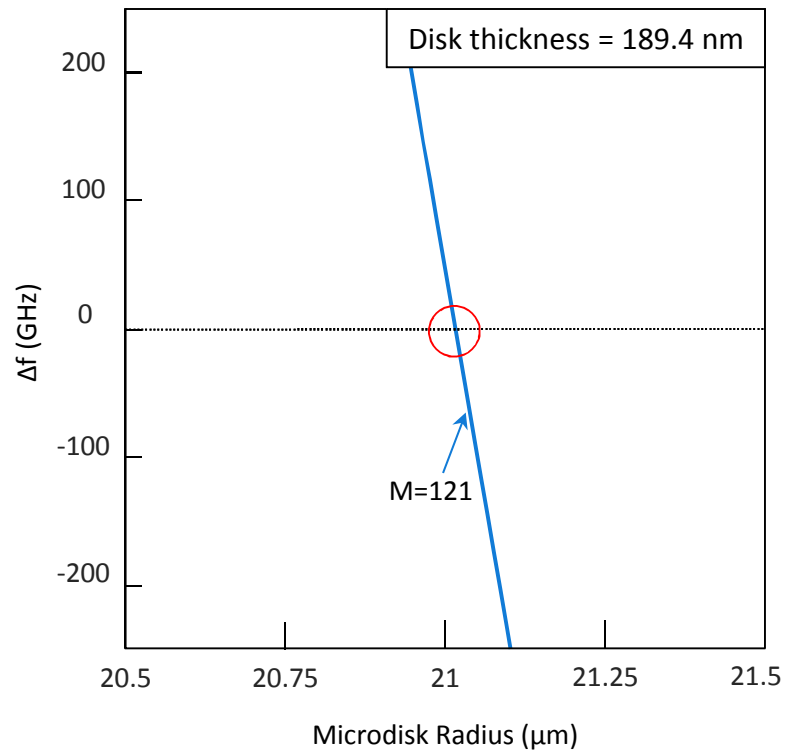
Geometric Phase Matching

Phase matching algorithm



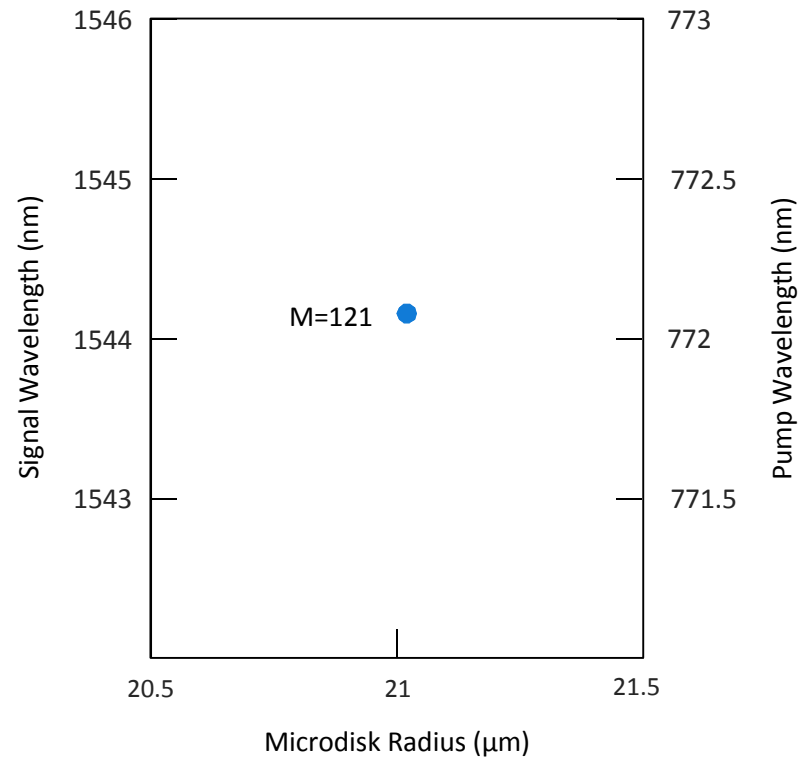
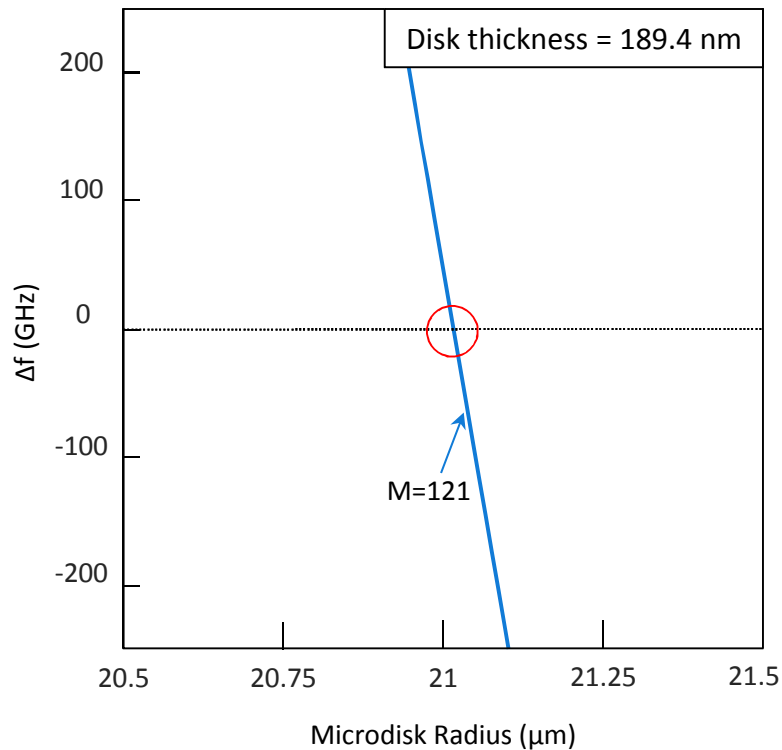
Geometric Phase Matching

Phase matching algorithm



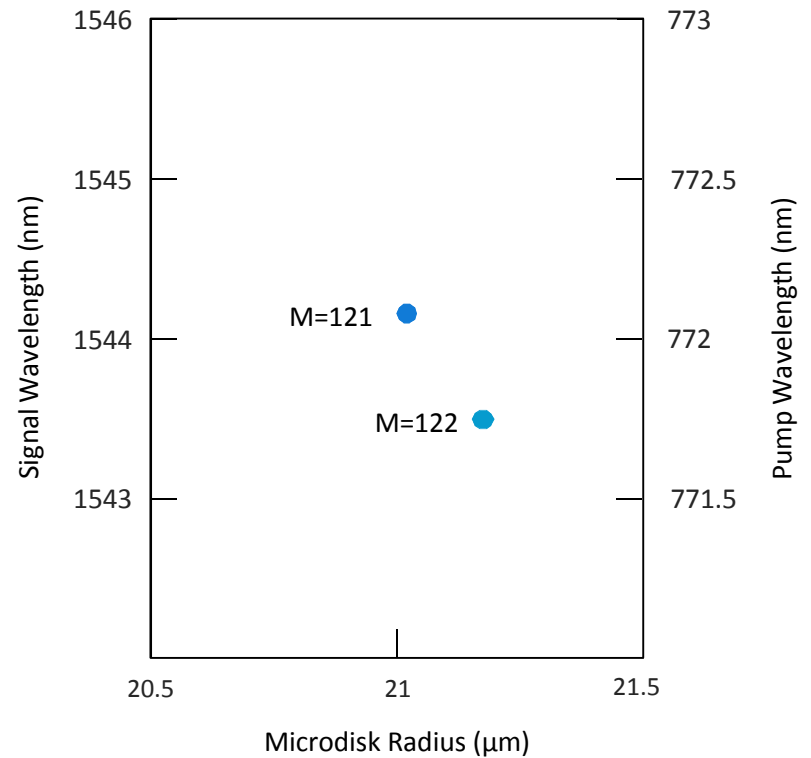
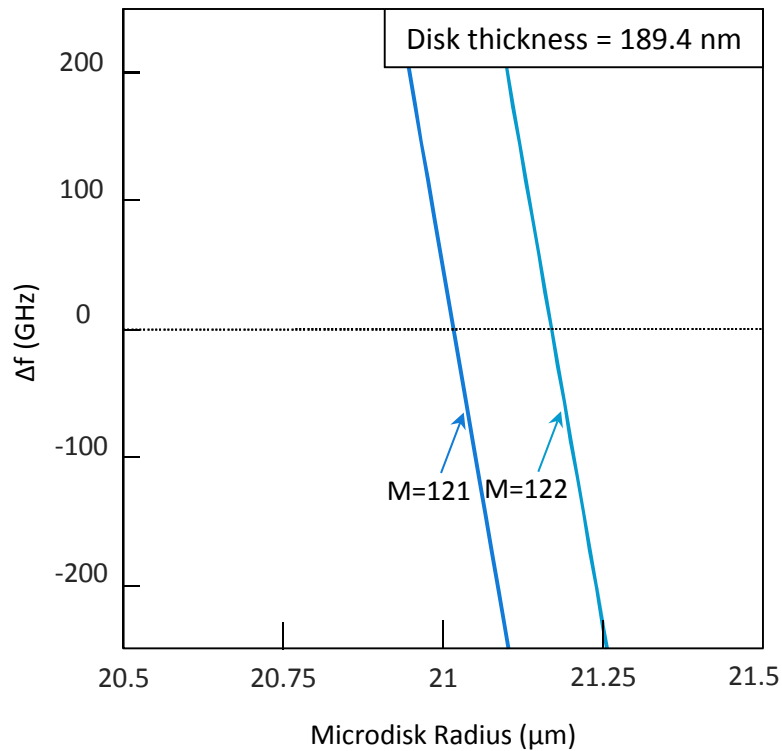
Geometric Phase Matching

Phase matching algorithm



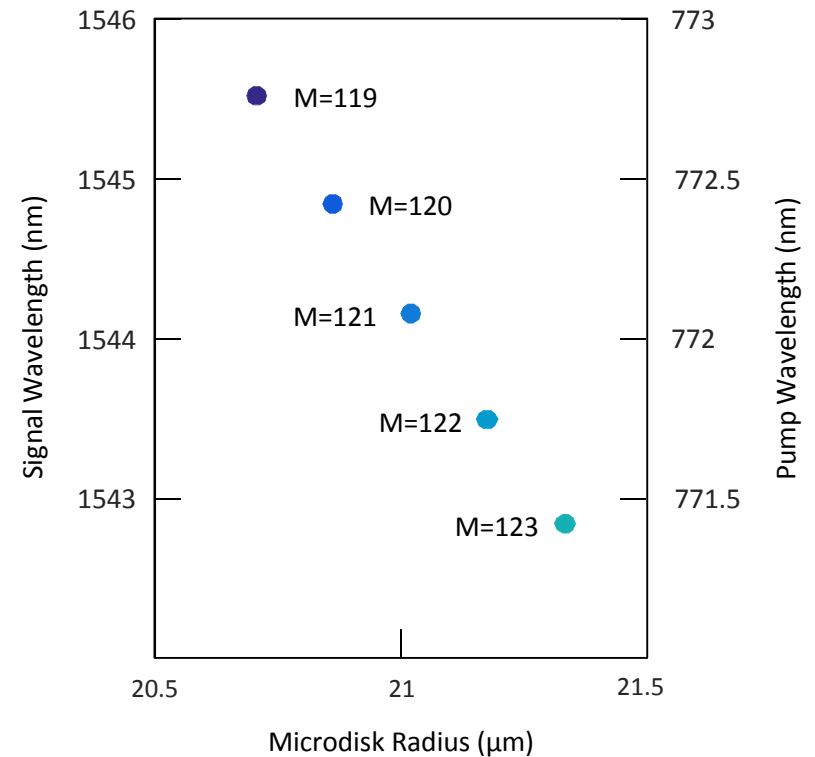
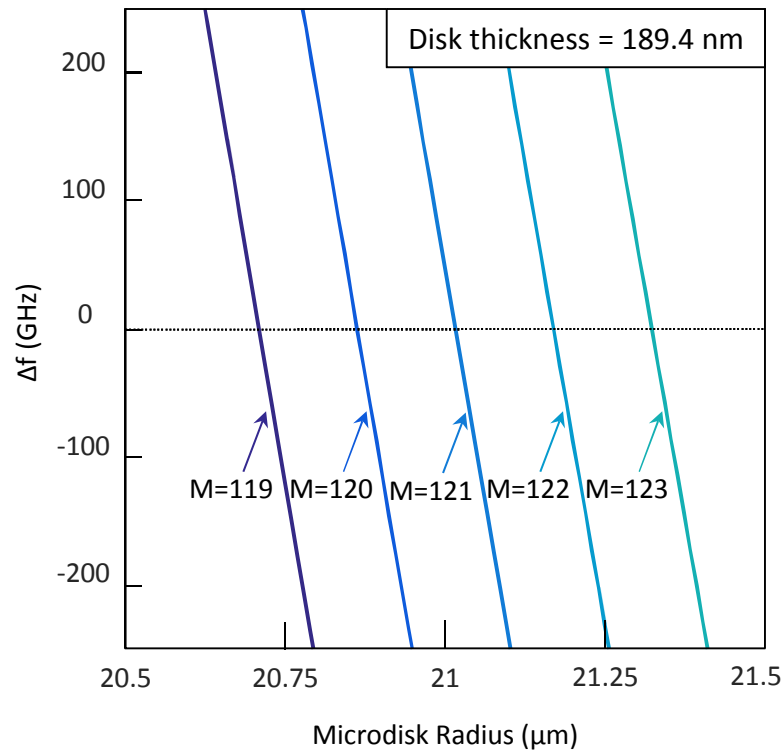
Geometric Phase Matching

Phase matching algorithm



Geometric Phase Matching

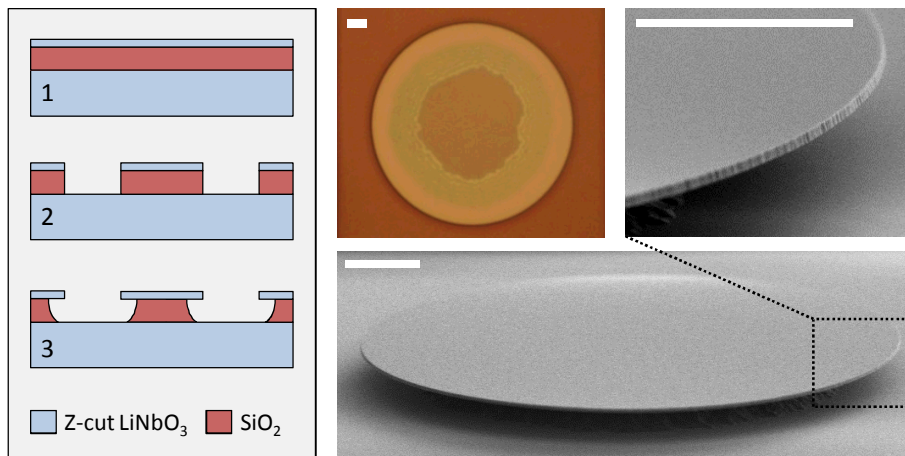
Phase matching algorithm



LiNbO₃ on Insulator (LNOI) Microdisks

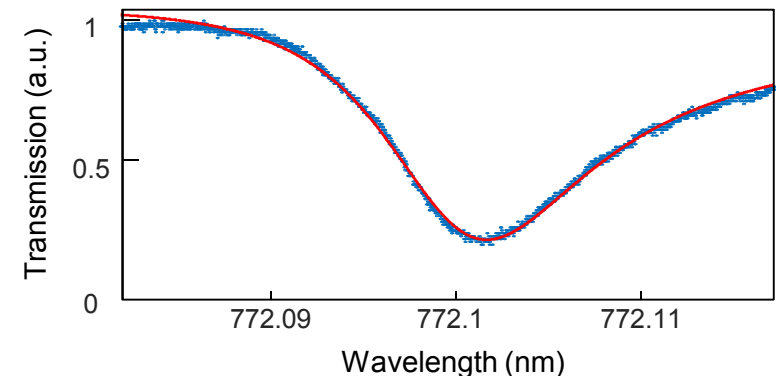
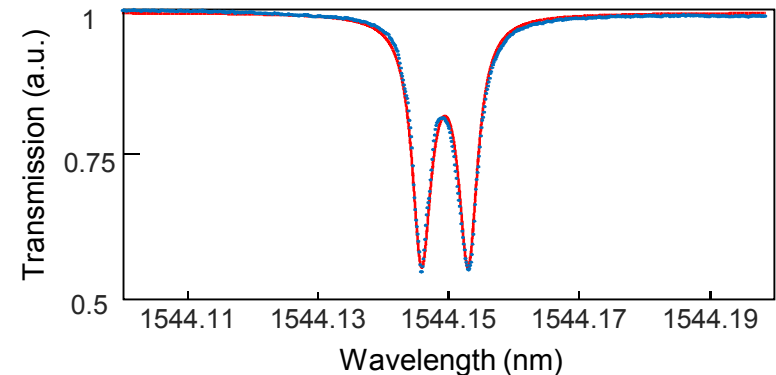
Fabrication Process

- 1) LNOI wafer
 - 200nm/2μm/0.5mm
 - LiNbO₃/SiO₂/LiNbO₃
- 2) Pattern, etch
 - Optical lithography
 - Argon plasma etch to define disks
- 3) Undercut etch
 - Vapor HF undercut to release disks

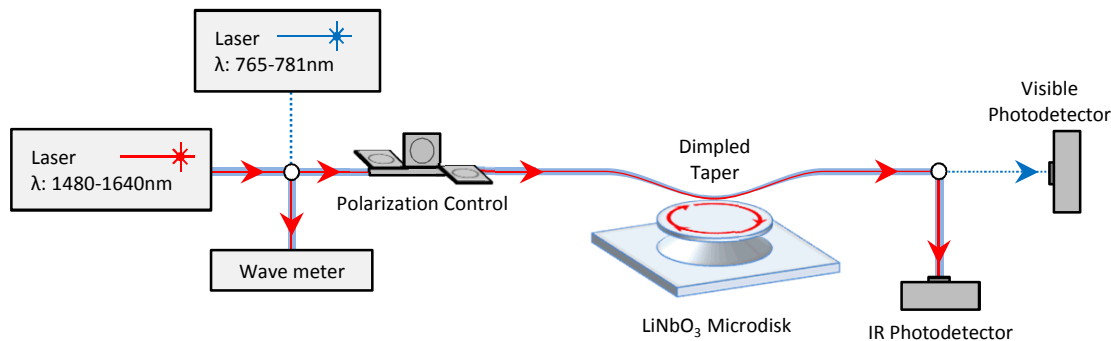


Optical Quality Factor

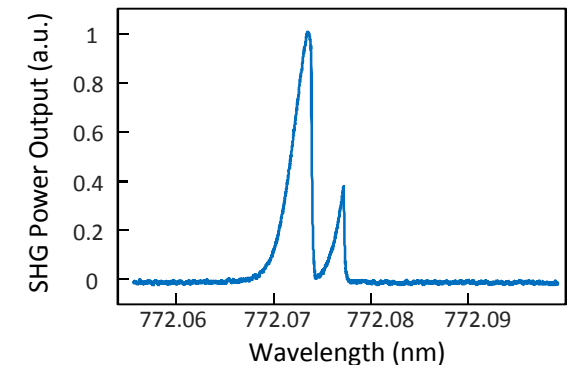
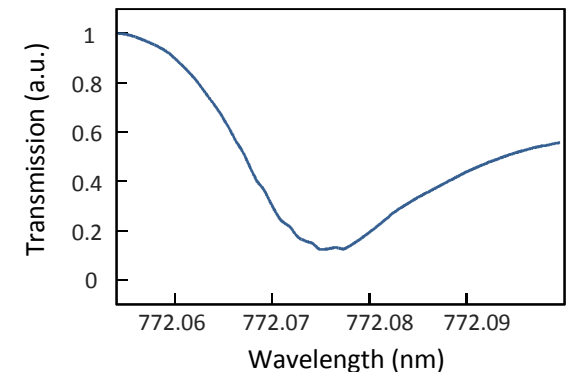
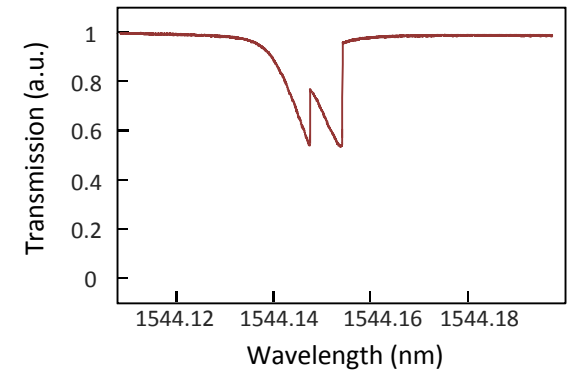
- $Q_{1550} = 570,000$
- $Q_{775} = 75,500$



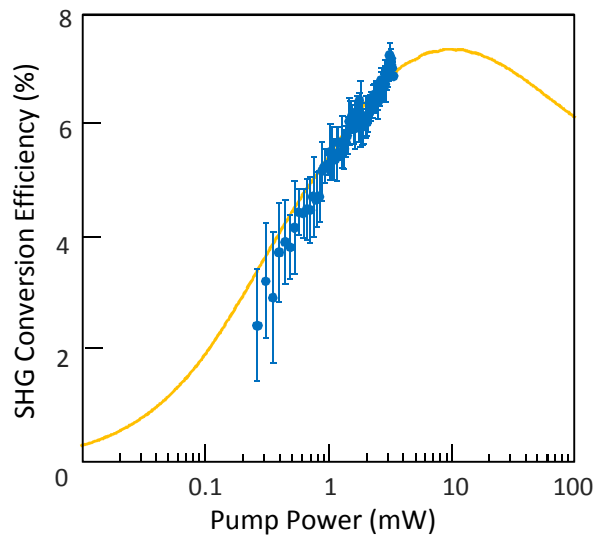
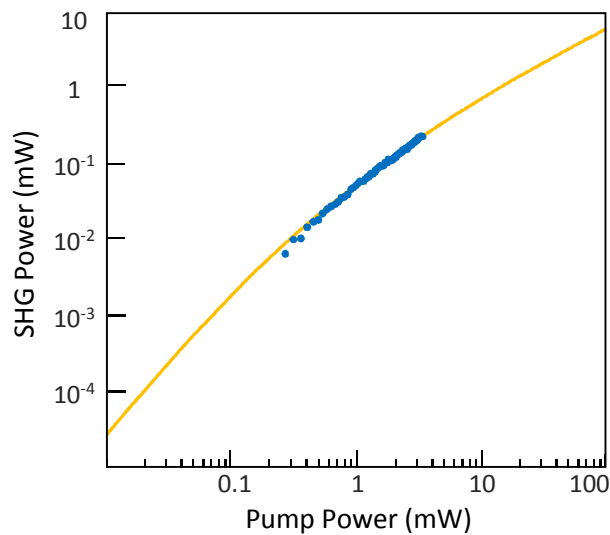
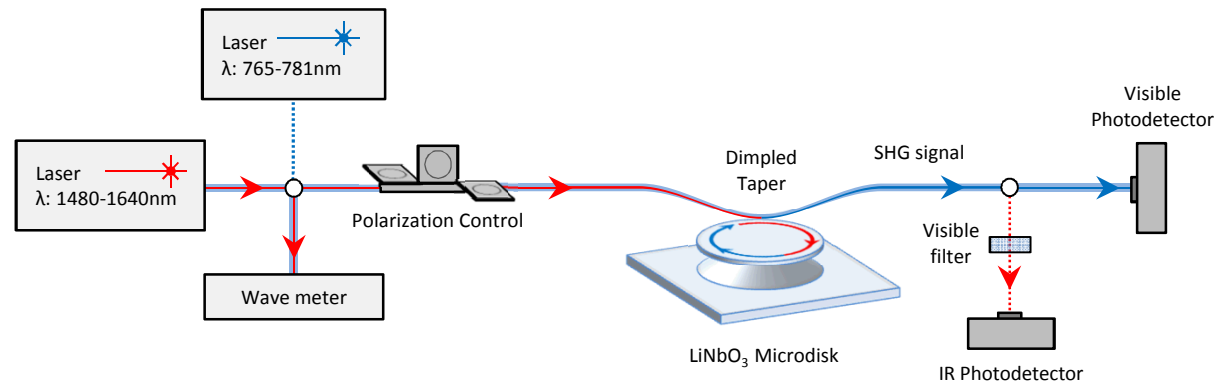
Experimental Confirmation of Phase Matching



- Energy conservation
 - Spectral overlap of pump and signal resonator modes
- Momentum conservation
 - M_{pump}, M_{signal} verified from transmission spectra, FEM modeling
 - $M_{pump} = 242$
 - $M_{signal} = 121$

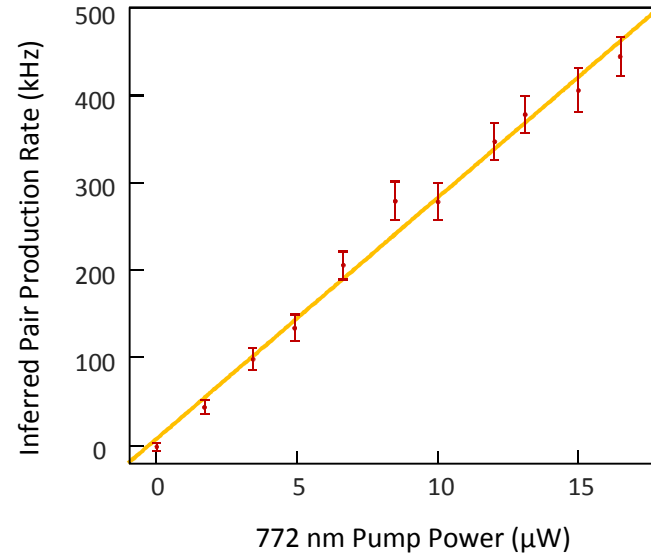
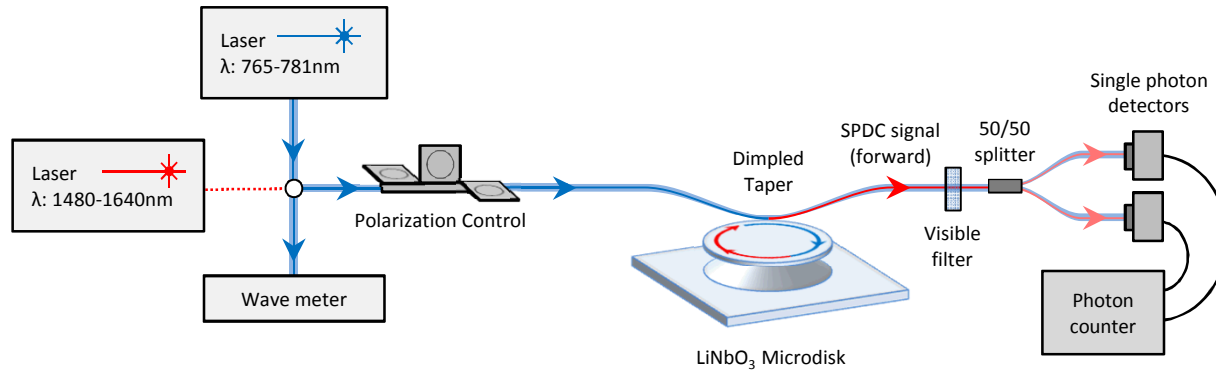


Second Harmonic Generation



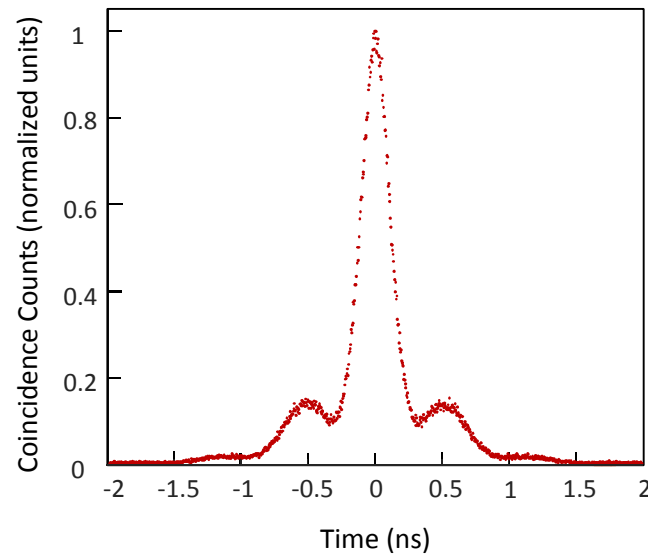
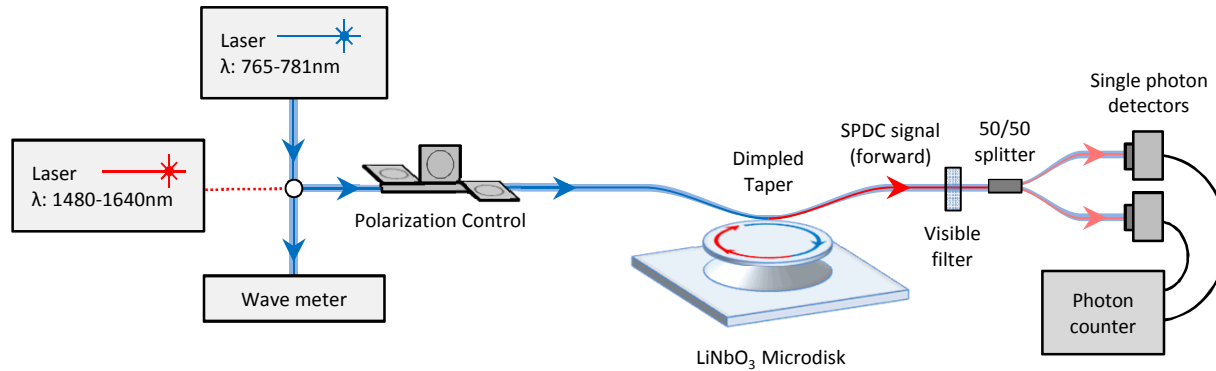
- Identical phase matching for SHG/SPDC
- $1550\text{nm} \rightarrow 775\text{nm}$
 - Efficiency = 7.8%
 - $P_{\text{pump}} = 3.14\text{mW}$

SPDC Pair Production

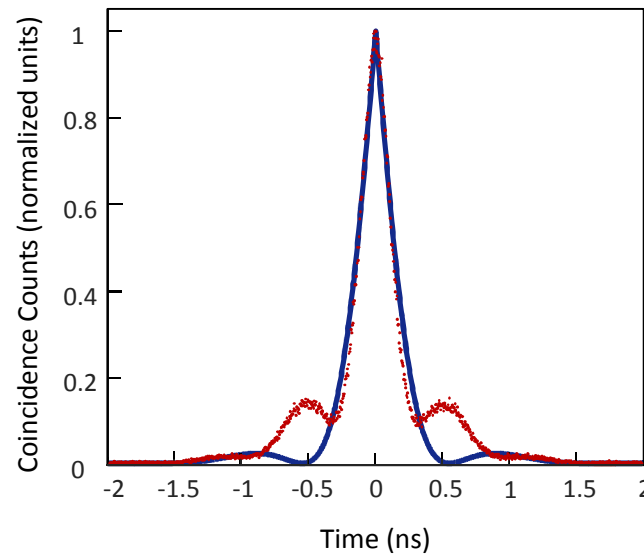
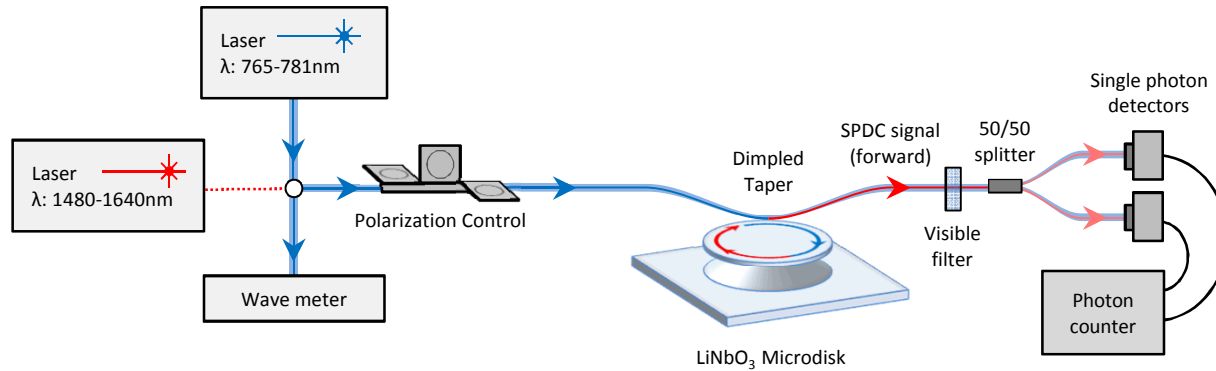


Conversion efficiency = 6×10^{-9}
Pair production rate = $27\text{kHz}/\mu\text{W}$

SPDC Coincidence (Forward Direction)

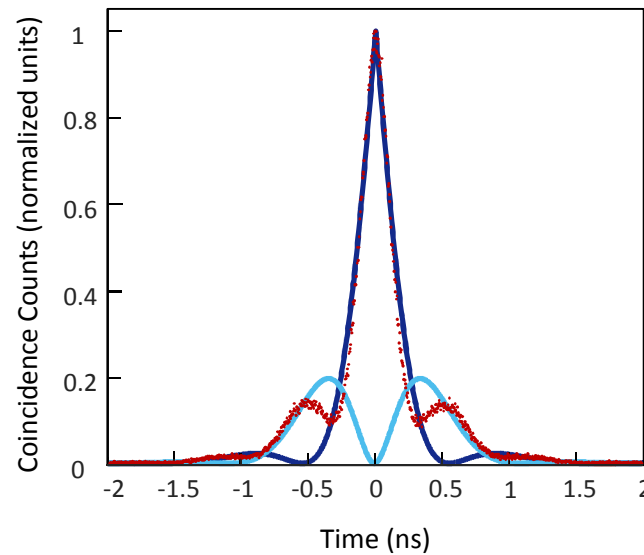
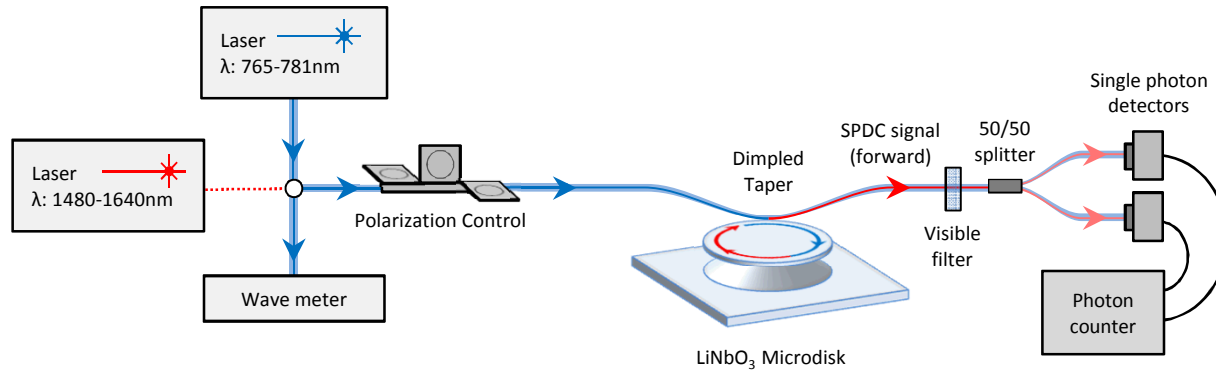


SPDC Coincidence (Forward Direction)



$$y = |\cos(\kappa_{BS} t) e^{-k_{tot} t}|^2$$

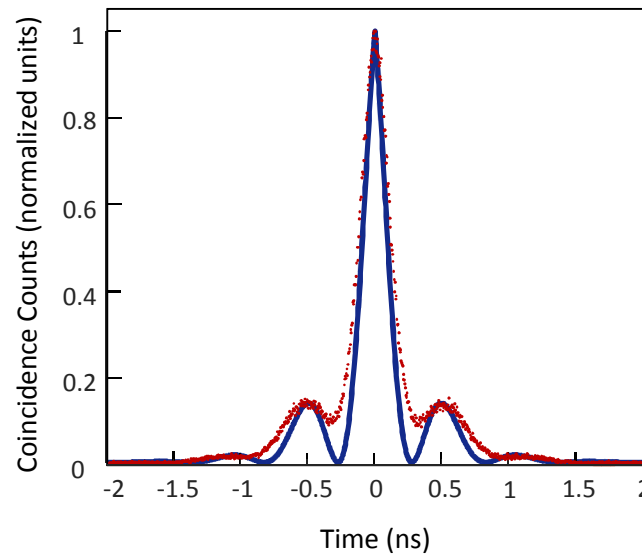
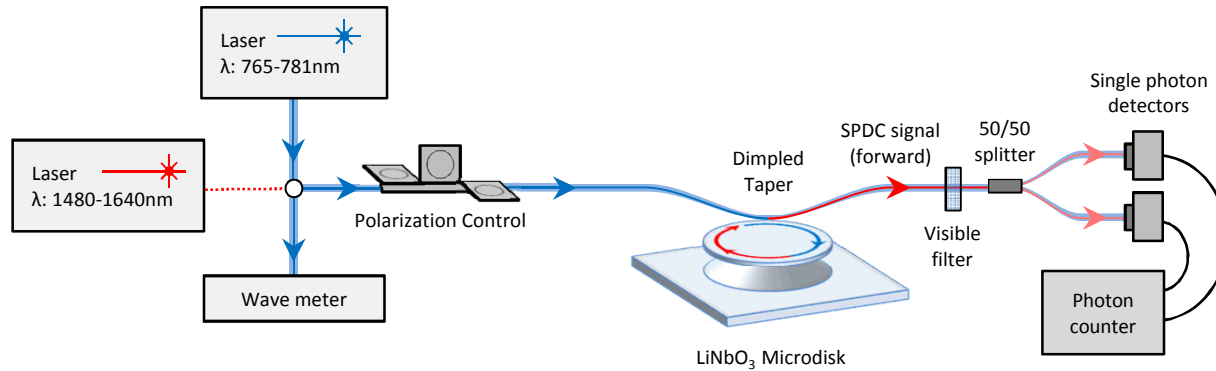
SPDC Coincidence (Forward Direction)



$$y = |\cos(\kappa_{BS} t) e^{-k_{tot} t}|^2$$

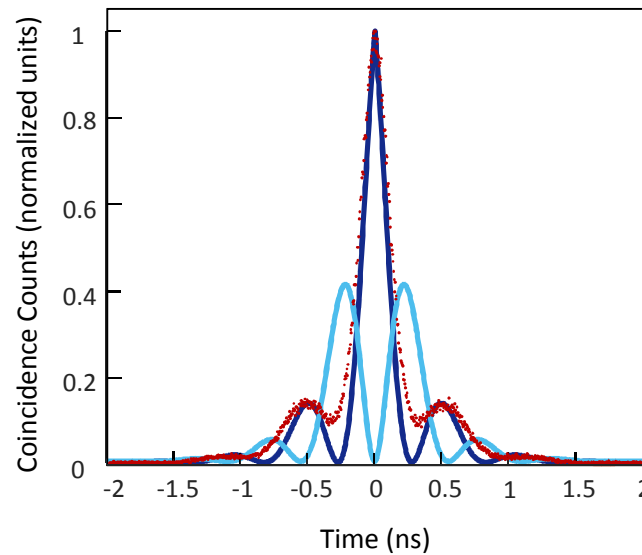
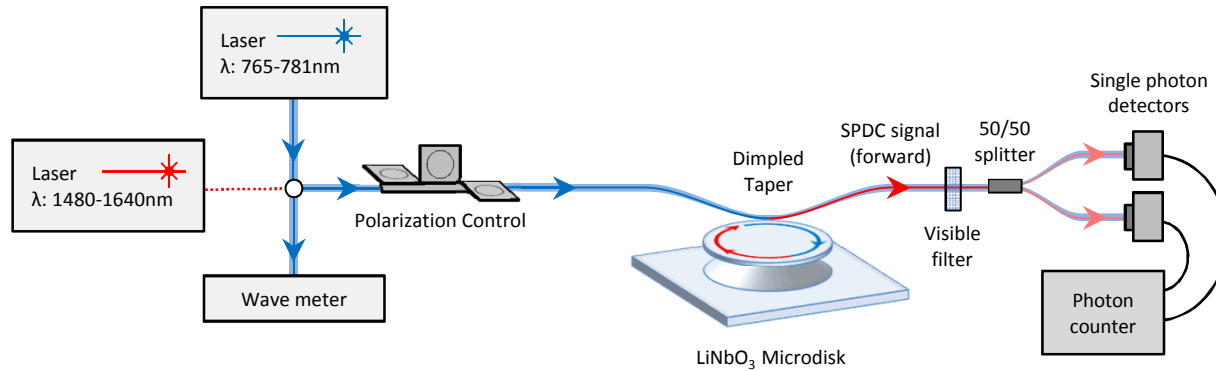
$$y = |\sin(\kappa_{BS} t) e^{-k_{tot} t}|^2$$

SPDC Coincidence (Forward Direction)



$$y = |\cos(2 \kappa_{BS} t) e^{-k_{tot} t}|^2$$

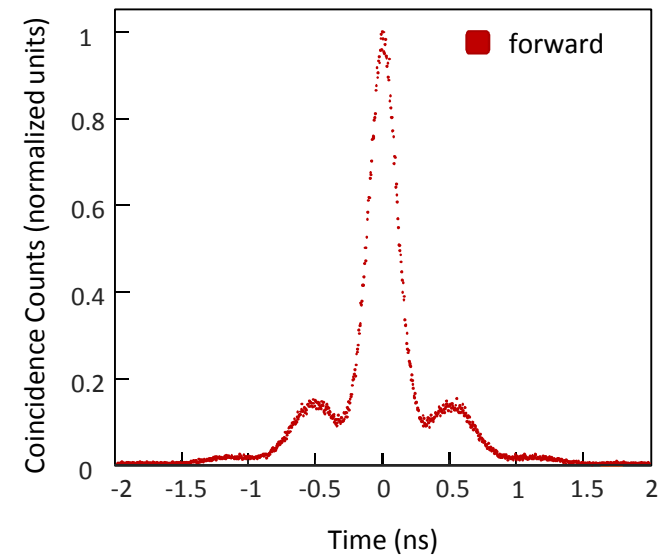
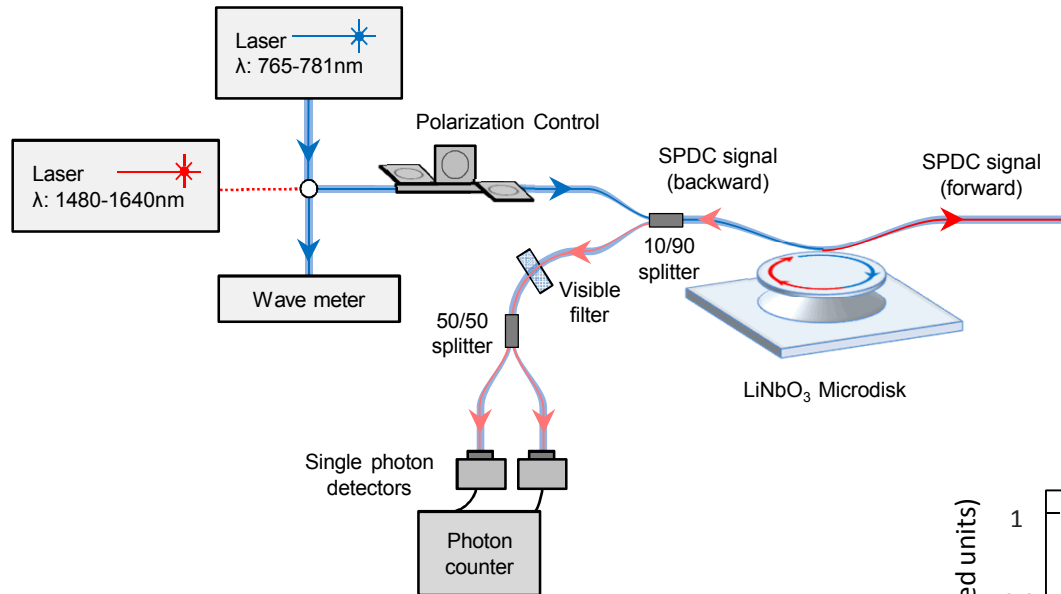
SPDC Coincidence (Forward Direction)



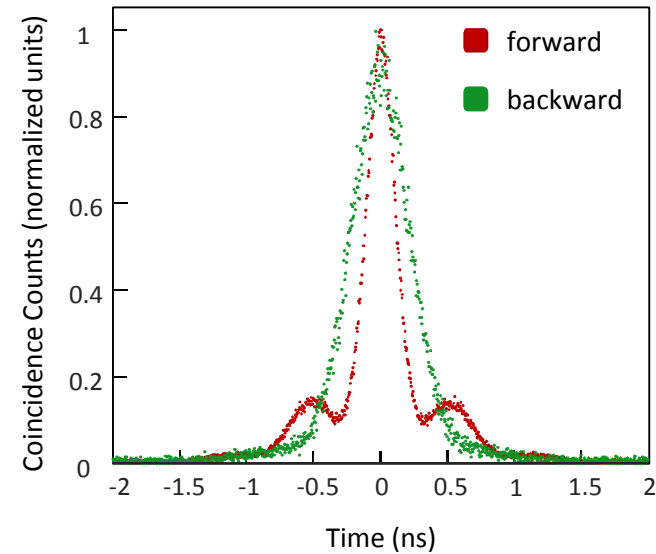
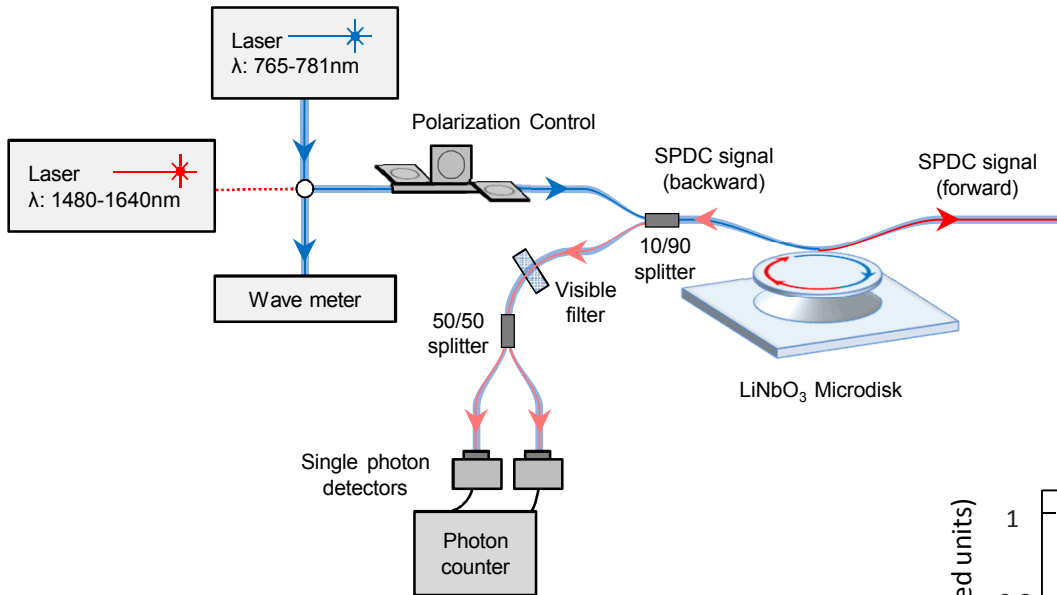
$$y = |\cos(2 \kappa_{BS} t) e^{-k_{tot} t}|^2$$

$$y = |\sin(2 \kappa_{BS} t) e^{-k_{tot} t}|^2$$

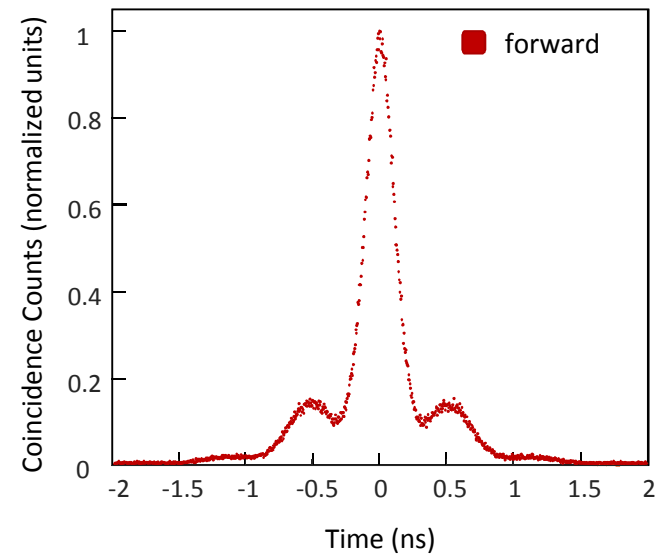
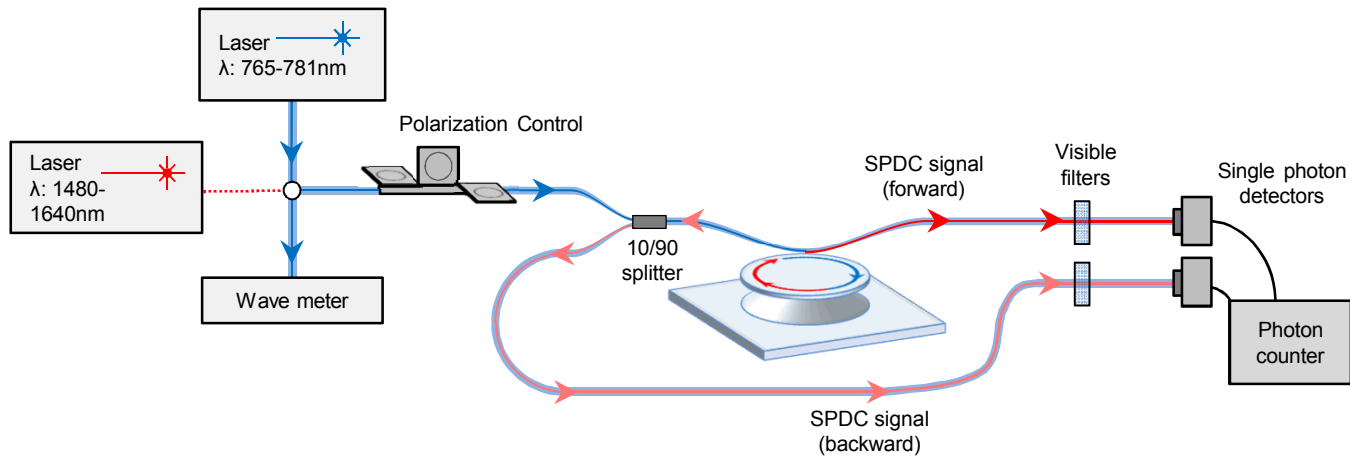
SPDC Coincidence (Backward Direction)



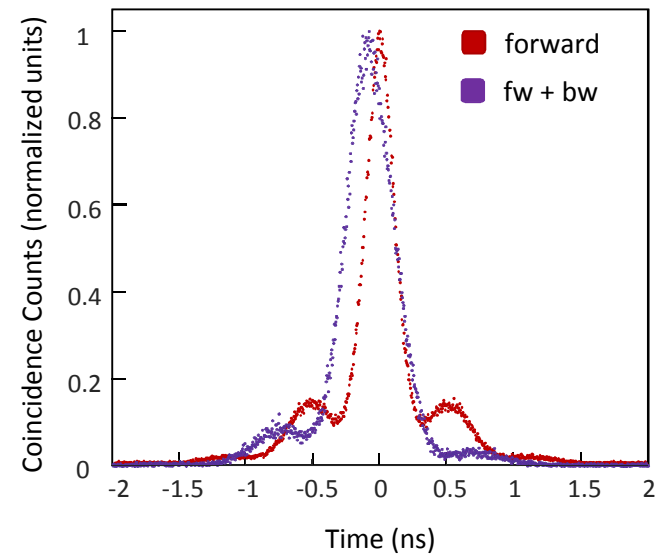
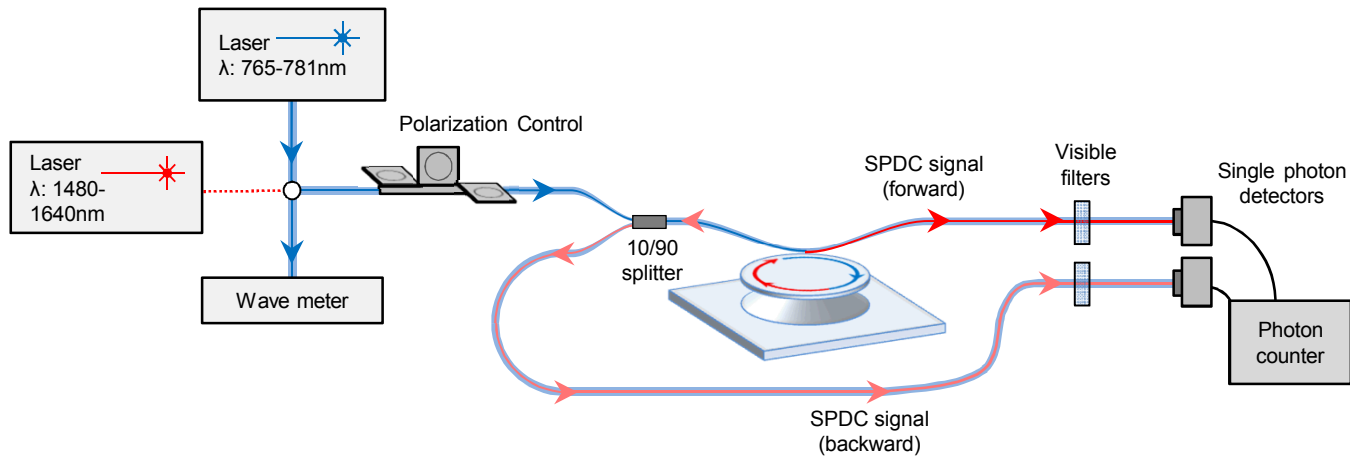
SPDC Coincidence (Backward Direction)



SPDC Coincidence (Forward + Backward)



SPDC Coincidence (Forward + Backward)



Conclusion

- LNOI microdisks for nonlinear frequency conversion
 - Geometric phase matching
- SHG
 - 1550nm $\rightarrow$ 775 nm
 - 7% conversion efficiency at 3.1mW input power
- SPDC
 - 775 nm $\rightarrow$ 1550nm
 - Conversion efficiency = 6×10^{-9}
 - Pair production rate = $27\text{kHz}/\mu\text{W}$
 - Interesting coincidence behavior due to coherent backscattering

Thank You!