Center for Quantum Networks
NSF Engineering Research Center

Quantum Network Integrated Devices and Systems

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Funded by National Science Foundation Grant #1941583

Course outline

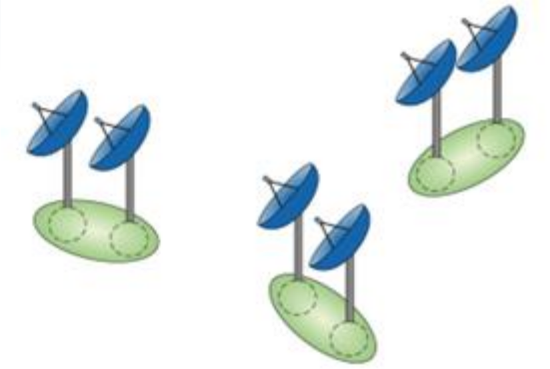
1. Introductions and Motivations
2. Quantum networks and EPR pair distribution
3. Waveguide Basics

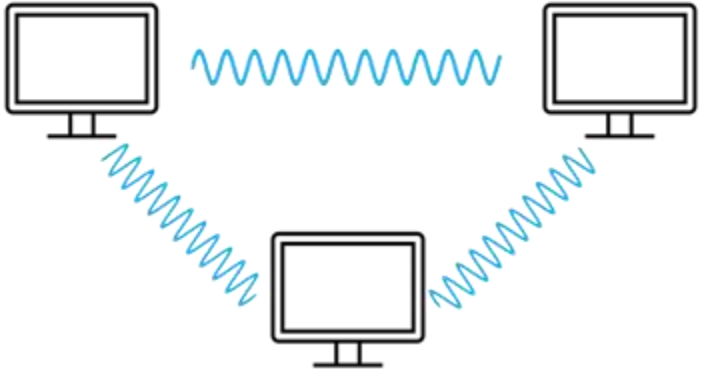
15-20 minute break

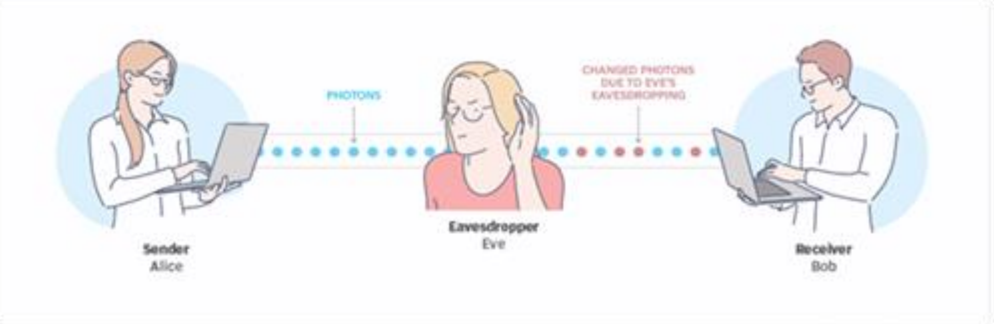
1. Materials and Geometries
2. Fabrication of photonic devices
3. Current device applications

Introduction

- Distributed quantum computing
- Clock synchronization
- Quantum-enhanced sensing
- Secure communications

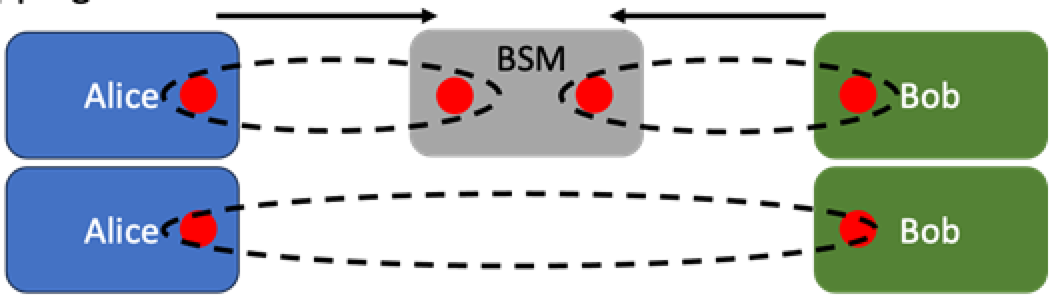




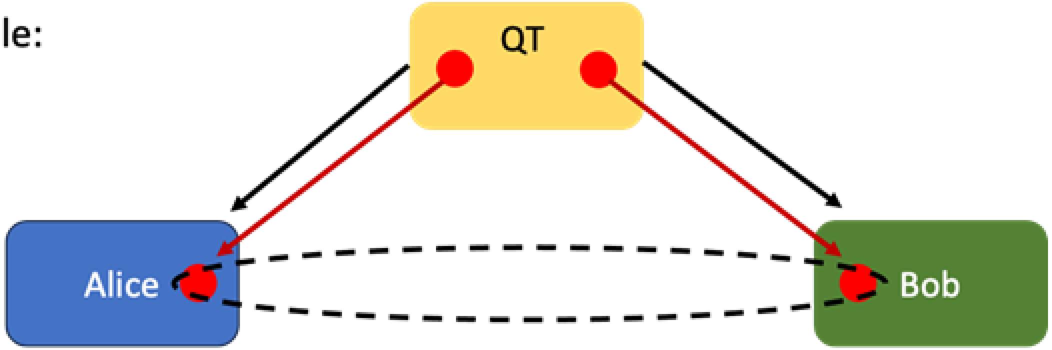


EPR-Pair distribution

Entanglement swapping:

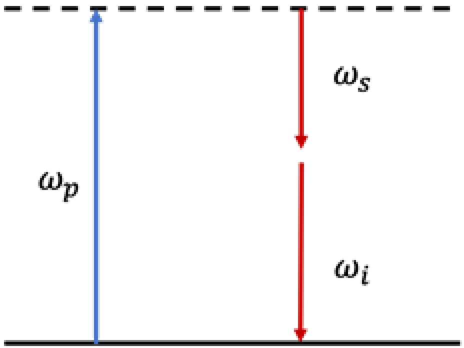


Source in the middle:



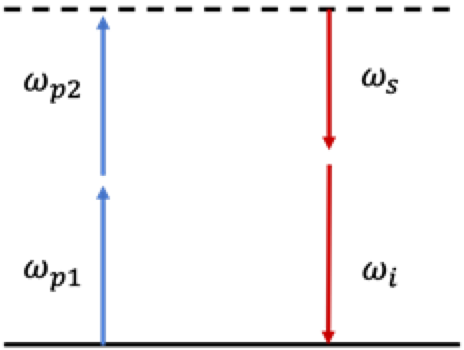
EPR pair generation

Spontaneous Parametric Down Conversation (SPDC)

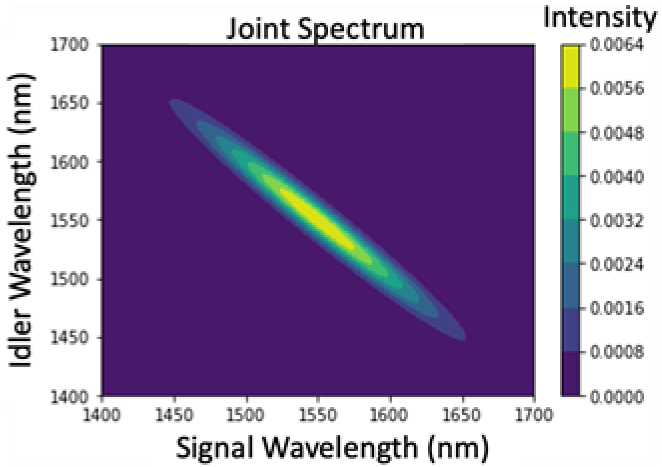


$$\omega_p = \omega_s + \omega_i$$

Four-Wave Mixing (FWM)



$$\omega_1 + \omega_2 = \omega_s + \omega_i$$



$\omega_p, \omega_{p1}, \omega_{p2}$: Pump frequencies

ω_s: Signal frequency

ω_i: Idler frequency

EPR pair generation

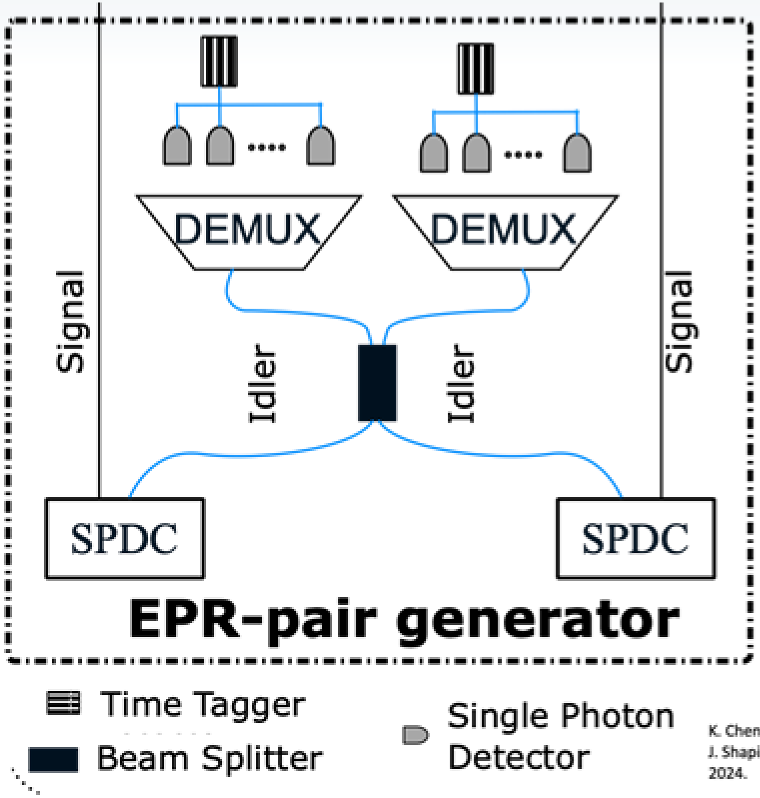
	SPDC	FWM
Nonlinear Order	**Second**	**Third**
Material accessibility	**Uncommon**	**Common**
Fabrication Capabilities	**Difficult**	**Easy**
Polarization Entanglement	**Yes**	**Yes**
Wavelength Entanglement	**Yes**	**Yes**
Phase matching	**Difficult**	**Easy**
Pump/EPR-pair waveband	**Visible/IR**	**IR/IR**
EPR-pair generation rate	**High**	**Low**

Zoom Poll - 1

1) In spontaneous parametric down-conversion, which statement best describes energy conservation?

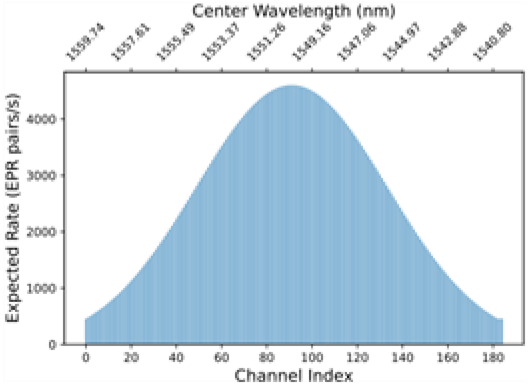
A. The signal photon always has higher energy than the pump
B. The pump photon splits into two photons whose total energy equals the pump energy
C. C. Energy is not conserved due to quantum fluctuations
D. The idler photon carries all the energy of the pump

EPR Pair Heralding



Heralding outcome:

- Signal photons wavelength information
- Confirmed polarization entanglement
- Registered timing/location of heralded EPR pairs in the network



K. Chen, et al. "Zero-added loss multiplexing for ground and space-based quantum networks", Physics review Applied, Vol 19, 5, 2023.
J. Shapiro, et al. "Entanglement source and quantum memory analysis for zero-added loss multiplexing", Physics Review Applied, Vol 22 4, 2024.

Network Nodes

Quantum Transmitter/Source Node:

EPR-pair generation
Heralding Bell-state measurement (BSM)
Mode converter?

Transmission link

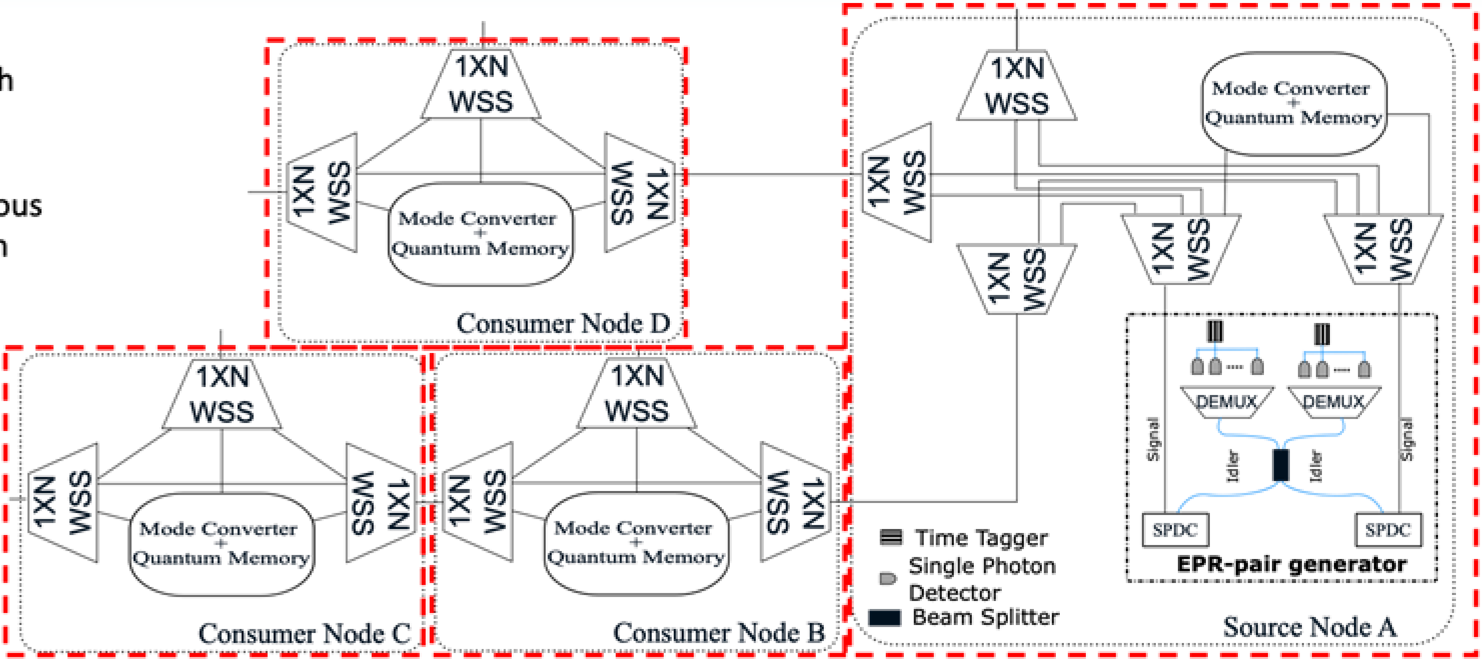
Quantum Receiver/Consumer Node:

Mode converters
Quantum memories

Network Nodes

WSS: Wavelength selective switch

SPDC: Spontaneous parametric down conversion



Zoom Poll - 2

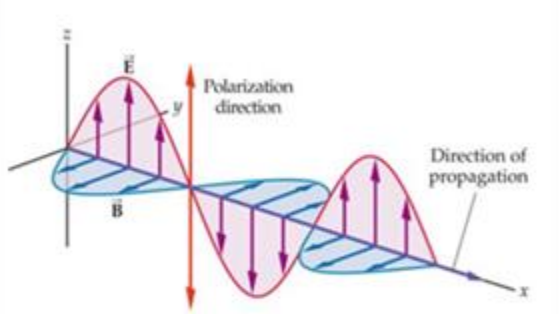
2) In the previous proposed network, which system cannot be included in a source node?

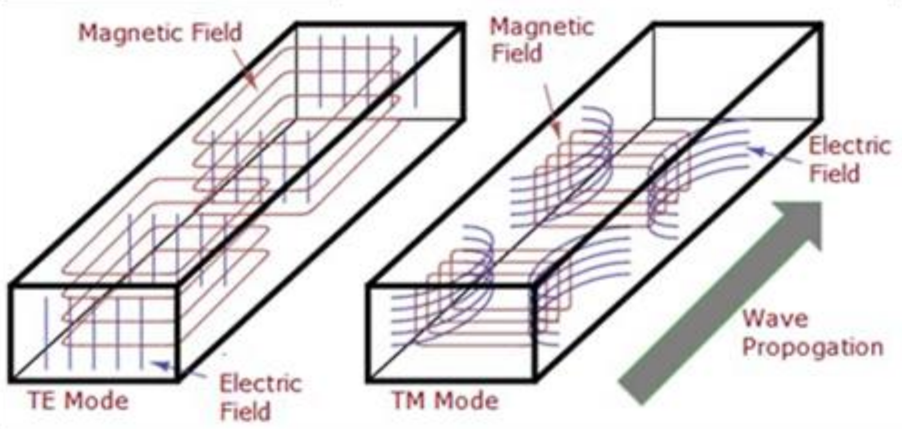
A. A mode converter
B. Quantum memory
C. Bell-State measurement
D. EPR-pair generator
E. Wavelength Selective Switch (WSS)

Links - transmission considerations

Free space, fiber, photonics integrated circuits (PICs)

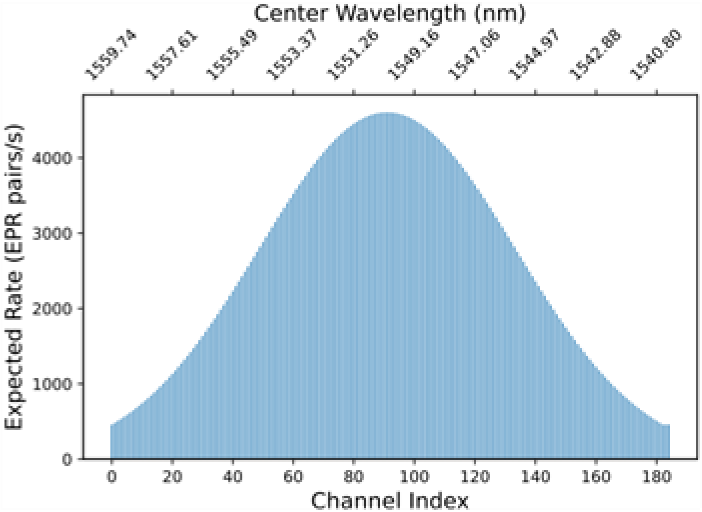
- Transmission loss
- Polarization considerations
- Path manipulation

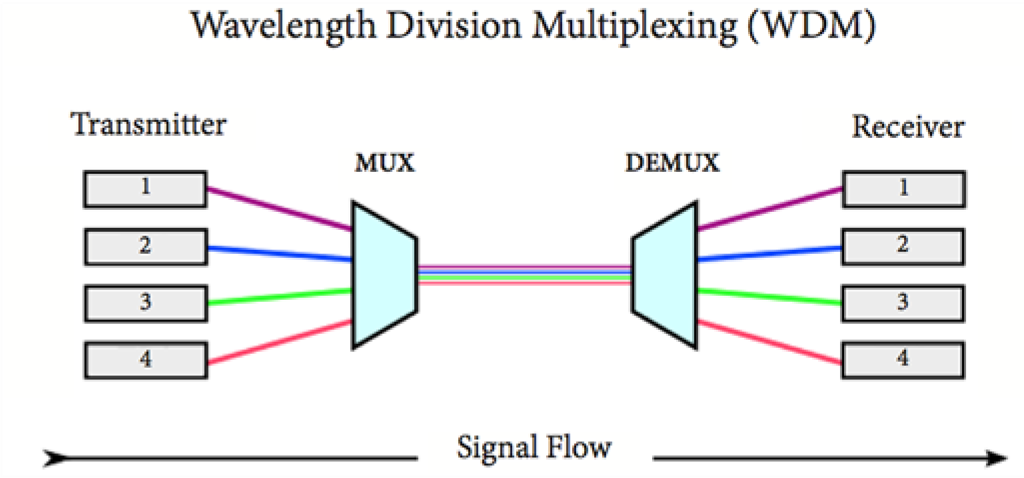




Links - Routing considerations

- Wavelength division multiplexing
  - Transmission and routing across the network



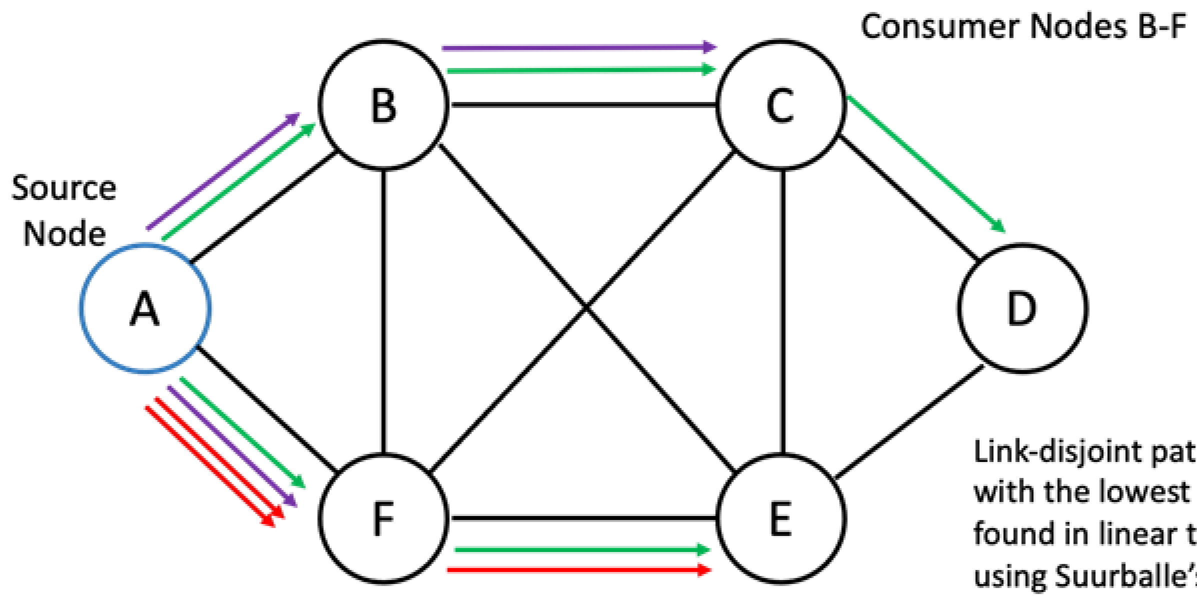


Zoom Poll - 3

3) Compared to free-space propagation, waveguides primarily offer:

A. Higher speed of light
B. No losses
C. Infinite bandwidth
D. Reduced diffraction and controlled propagation

Routing in repeaterless EPR- distribution networks



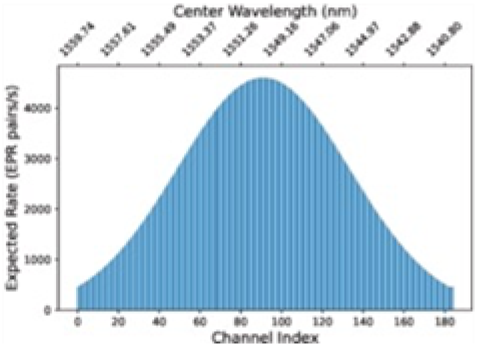
Link-disjoint paths with the lowest loss found in linear time using Suurballe's algorithm

Consumer Pair	Loss given source at A
A-B	34 dB
A-C	34 dB
A-D	54 dB
B-C	52 dB
B-D	91 dB
C-D	74 dB

R. Bali, et al. "Routing and spectrum allocation in broadband entanglement distribution", Journal of Selected Areas in Communications (JSAC), Accepted with Major revisions, 2024.
R. Bali, et al. "Routing and Spectrum allocation in broadband EPR-pair distribution", IEEE International Conference on Communications (ICC), 2024.

Spectrum Allocation

Maximize over assignments, the minimum number of photon pairs received by any consumer pair after loss.

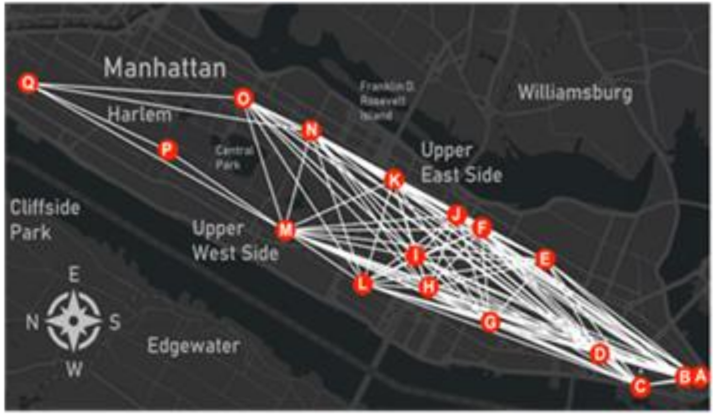


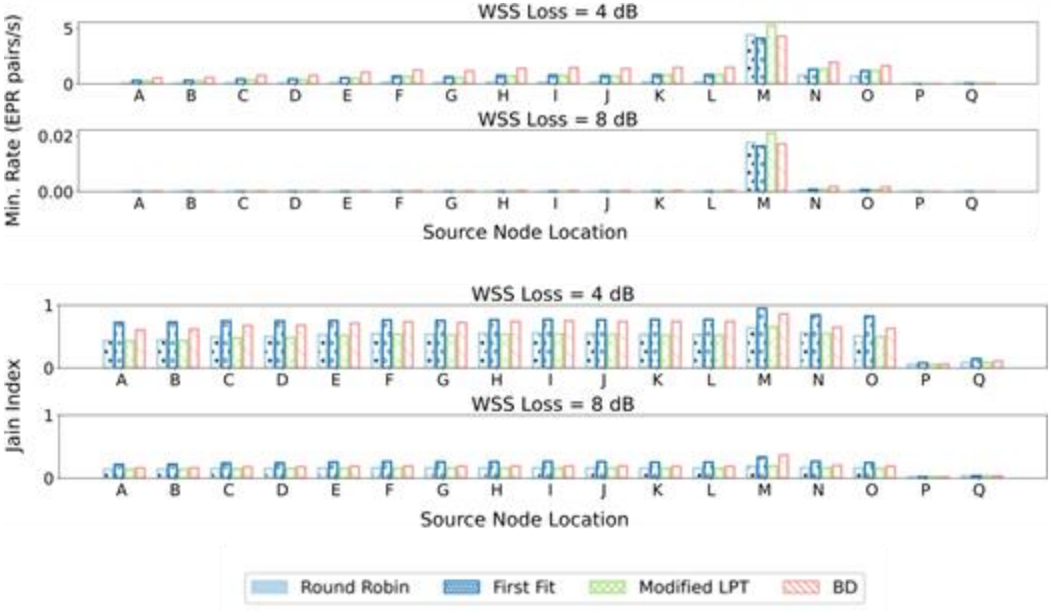
EPR-Pair Rate	Channel
458	200
458	199
⋮	⋮
4,584	100
⋮	⋮
458	1

Consumer Pair	Loss given source at A
A-B	34 dB
A-C	34 dB
A-D	54 dB
B-C	52 dB
B-D	91 dB
C-D	74 dB

Routing and Coexistence

Manhattan incumbent local carrier exchange (ILEC) network





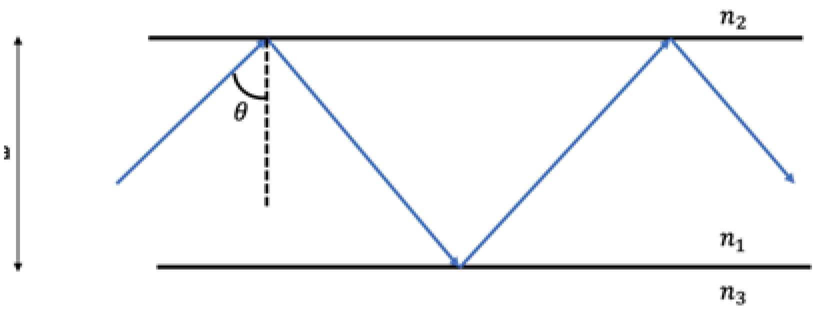
Real network configuration to test selected spectrum allocation algorithms.

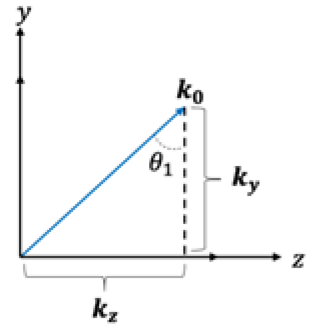
Waveguide Basics

Snell's Law: $n_1 sin\theta_1 = n_2 sin\theta_2$

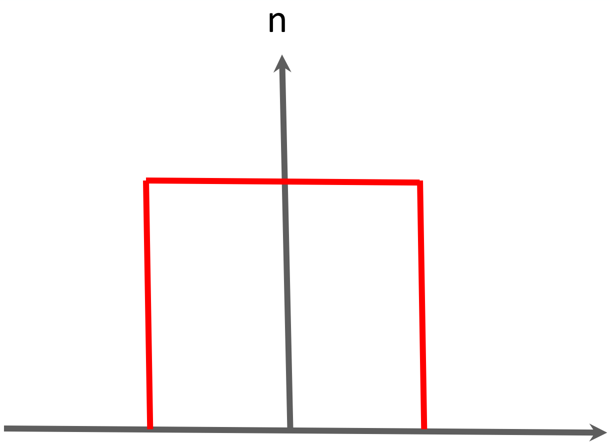
Critical angle: $sin\theta_c = \frac{n_2}{n_1}$

$$NA = n_1 sin\theta_c$$



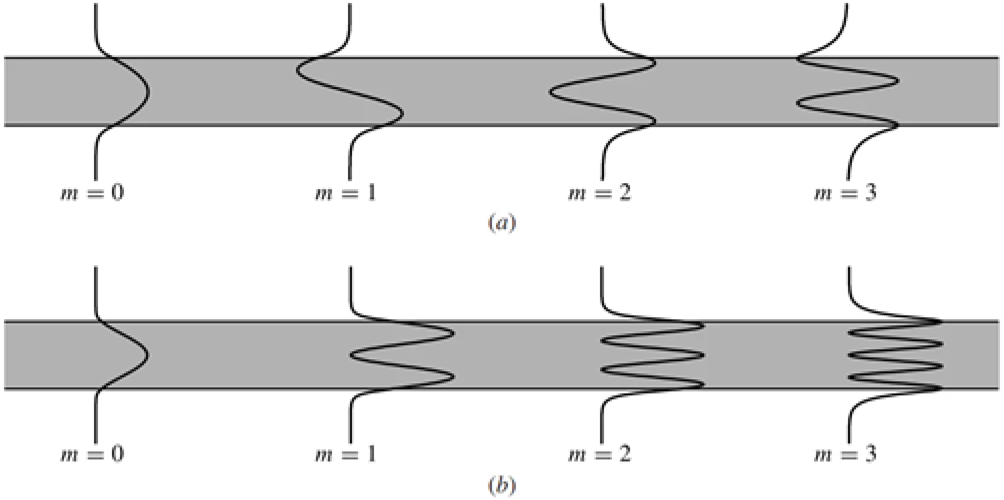


Waveguides Effective Index

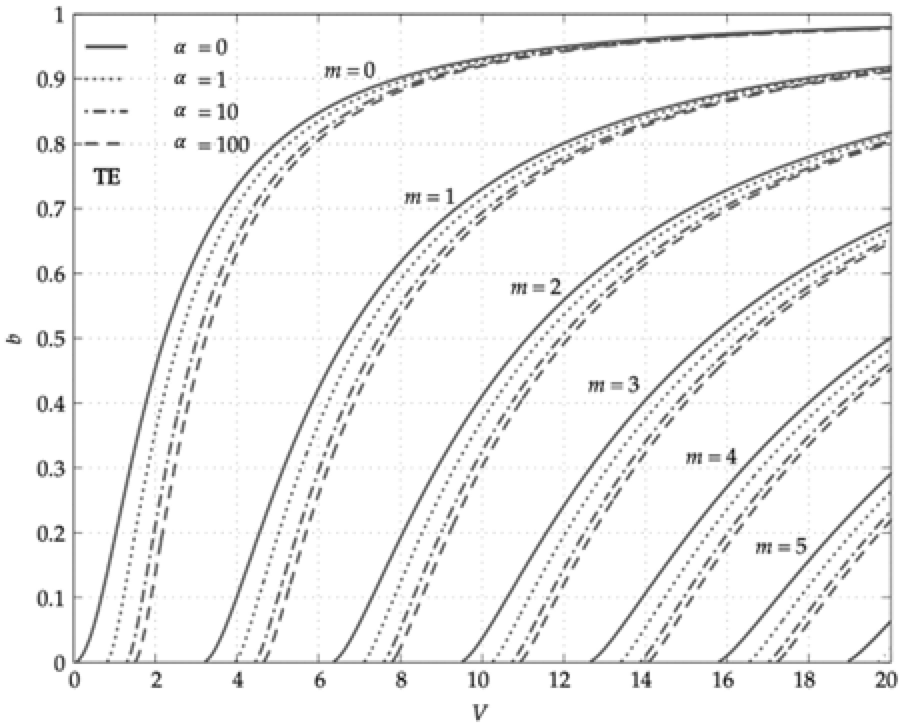


Phase constant: $\beta = n_{\text{eff}} \frac{2\pi}{\lambda}$

k vector: the vector describing the direction of propagation of a wave



Waveguide Modes



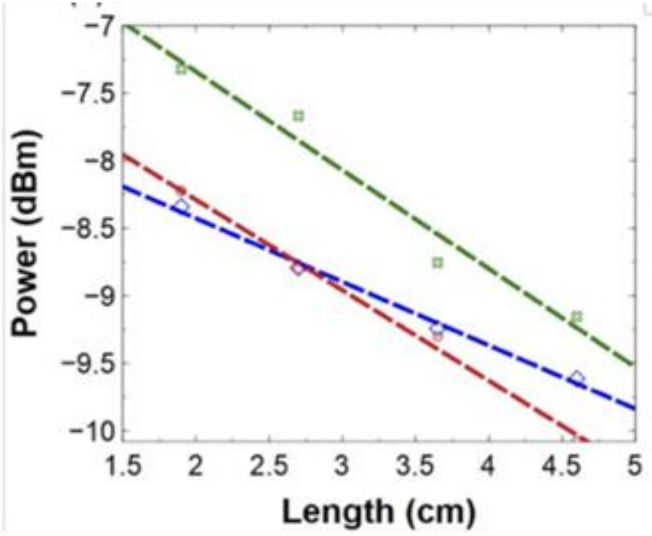
Zoom Poll - 4

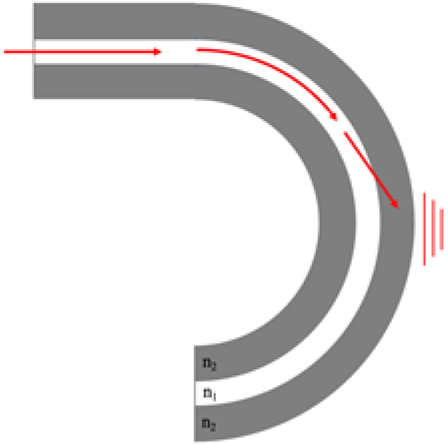
4) Why must the refractive index of the core be higher than that of the cladding?

A. To increase absorption in the core
B. To ensure total internal reflection occurs at the interface
C. To reduce scattering losses
D. To allow electrical current to flow

Waveguide Loss Mechanisms

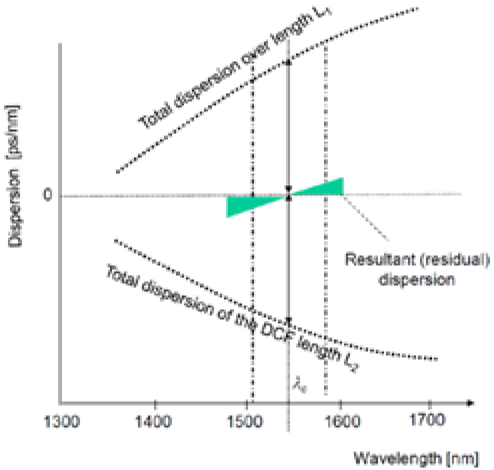
- Coupling loss
- Absorption
- Radiation
- Scattering
  - Rayleigh (<< λ)
  - MIE (~λ)

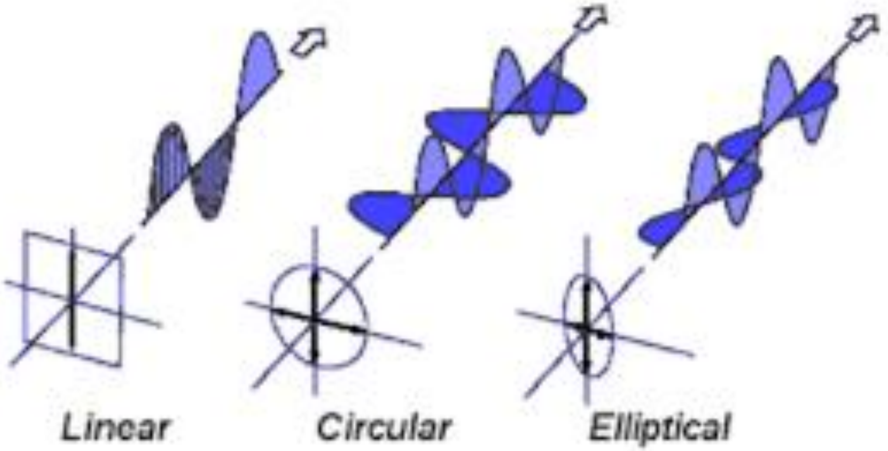




Polarization and Dispersion

- Dispersion
  - Spatial (modal)
  - Chromatic
  - Polarization





Zoom Poll - 5

6) Which type of dispersion arises because different field distributions travel at different speeds in a waveguide?

A. Material dispersion
B. Chromatic dispersion
C. Modal dispersion
D. Polarization dispersion

15 Minute Break!

Photonic devices, materials, and fabrication

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Types of Materials

Material:	Examples	Thin Film Deposition Process	Usual Benefits
Glass	Fused Silica (SiO_2), Chalcogenide glasses, Various doped glasses	CVD, Sputtering	Higher indexes
Polymer	Organic: PMMA, PC Inorgainc: Sulfur	Spin Coat	Higher thermo-optic coeff.
SOI	Silica (sometimes Sapphire) between Si layers		Full use of silicon properties

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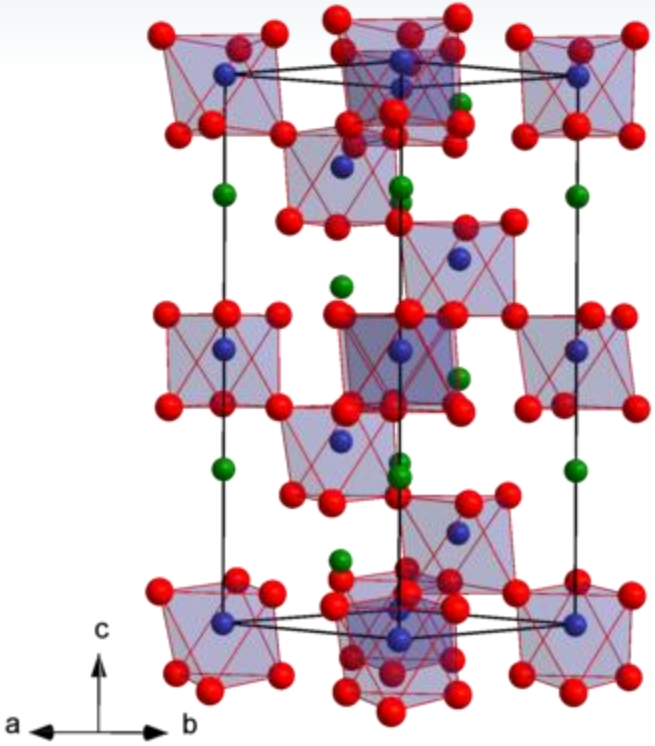
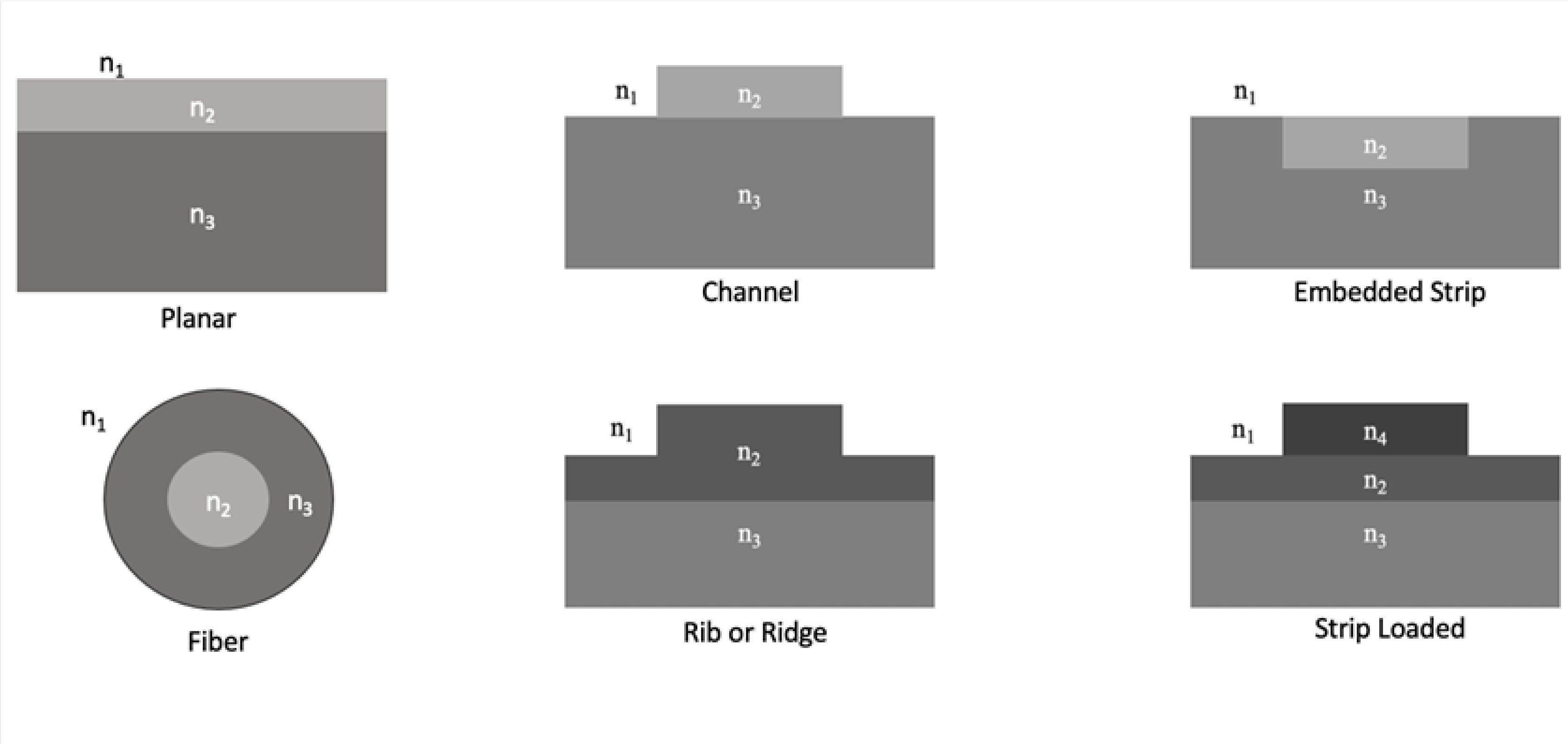
Thin Film Lithium Niobate (TFLN)

- Used as active source (SPDC)
  - Electro-optic response
- Refractive index of ~2.2
- Large mode confinement
- Small structures

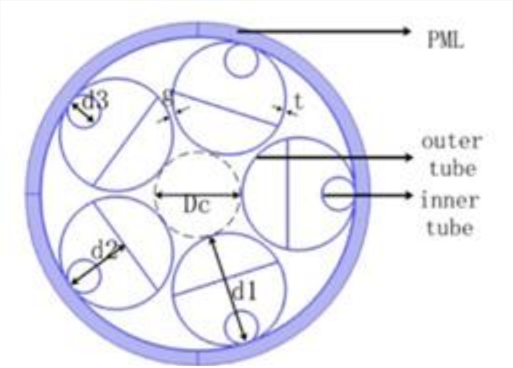


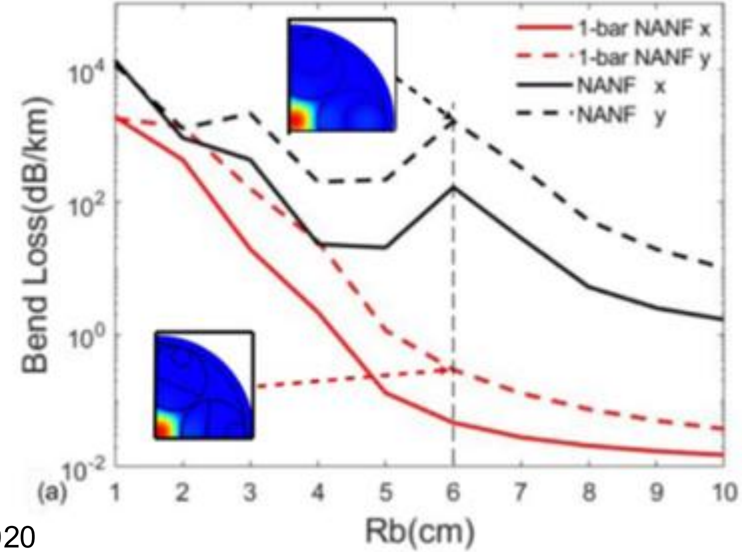
Common Waveguide Geometries



Hollow Core Fibers

- Decreased loss with hollow core fibers
  - 0.18 dB/km at 1550 nm
  - 0.22 dB/KM at 1310 nm
  - Potential for order of magnitude lower loss than common fibers today
- Increased bend loss - limits applications in metro network systems
- Minimize photon loss in quantum networks





Jasion et. al. OFC 2020

Other Technologies

Technology:	Usual materials	Thin Film Deposition	Usual Benefits
Fiber	Glasses above as core material	—	long propagation distances
Hollow Core Fiber	Same as solid core fibers	—	Low loss, low nonlinearities,
Crystalline	Same as other waveguide materials	Any	Frequency dependent propagation

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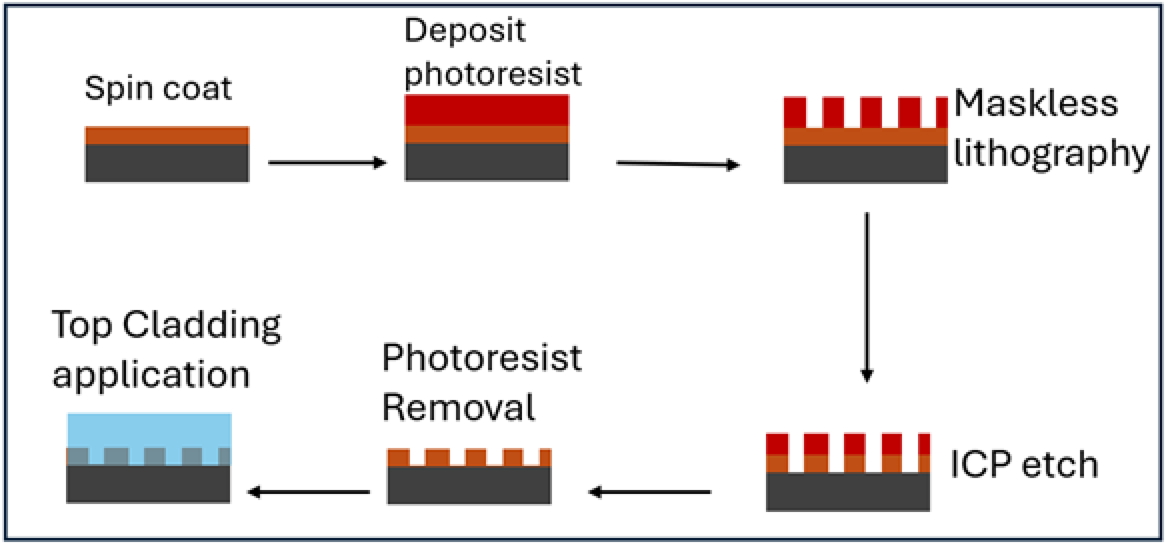
Fabrication



Clean room facilities

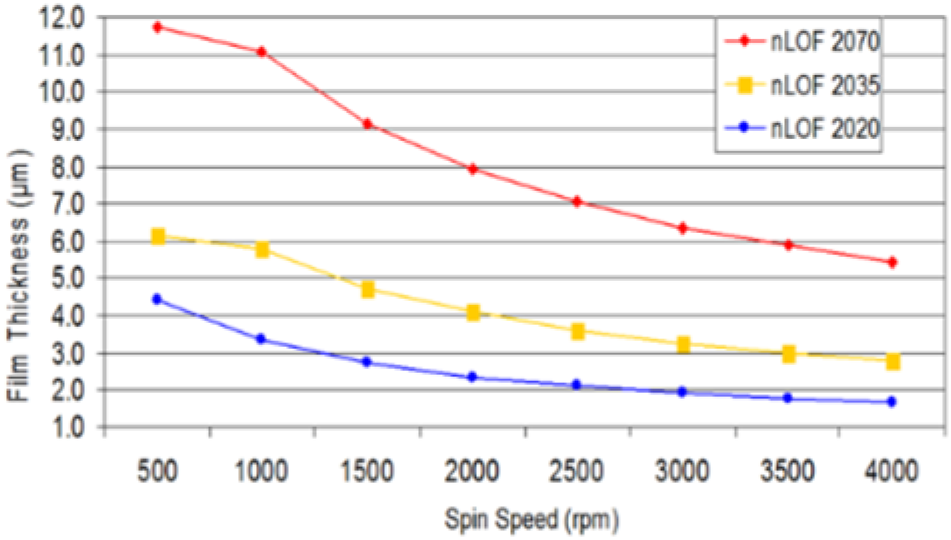
- Controlled environment minimizing dust
- PPE required: gown, gloves, etc…

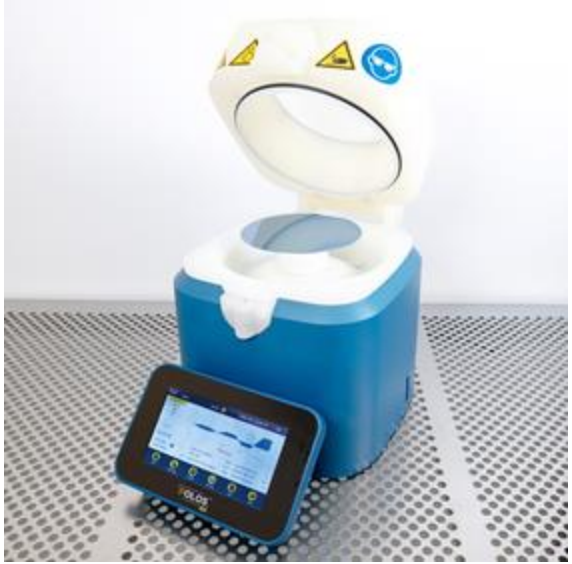
Material Deposition

- Spin coating
- CVD
  - Plasma-enhanced (PECVD)
  - Metal-Organic (MOCVD)
- Sputtering

Spin Coating

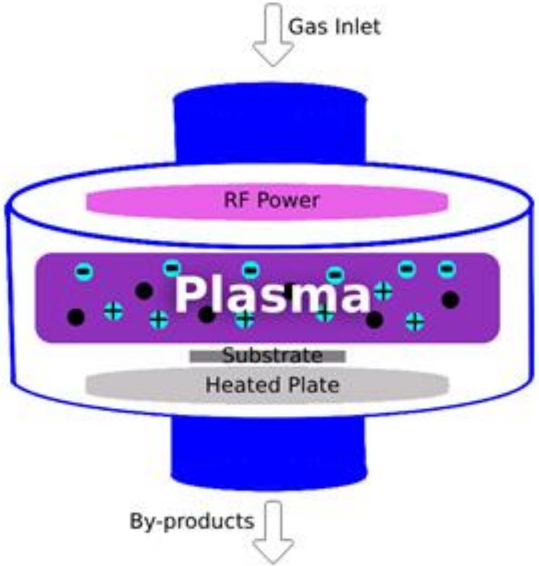
- Low cost, simple and fast process
- material must be in a liquid state (in solvent)





PECVD

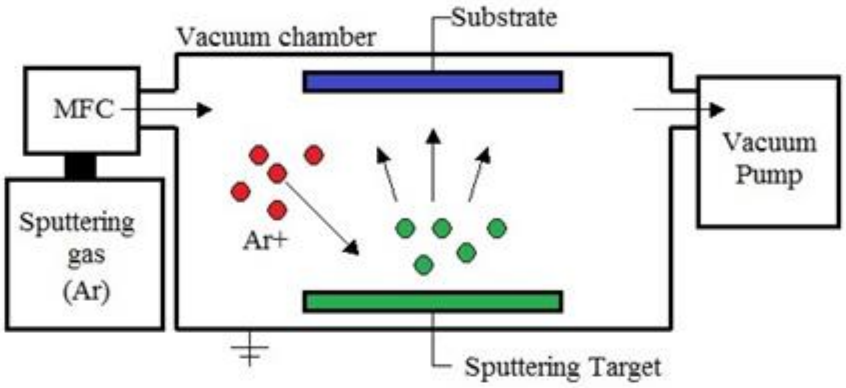
- Plasma Enhanced Chemical Vapor Deposition
- CVD:
  - precursor gases enter a vacuum chamber
  - interact with other injected gases
- PECVD:
  - lower temperatures due to the nature of the reaction
  - expanding the range of materials
  - faster deposition rates than CVD



https://www.ema3d.com/blog/pecvd-revolutionizing-thin-film-deposition/

Sputtering

- a solid target material can be:
  - heated/ evaporated
  - hit with an electron beam
  - hit with a high intensity laser
  - hit with an Ion Beam
- bombardment leads to an amount of material to launch towards the substrate.
- Good for electrodes/contacts



NanoStructured Coating Co.: https://pvd.ir/faq/

Zoom Poll 6

You are testing a polymer platform for photonic waveguide architectures. It is delivered dissolved in a liquid solvent, how would you deposit this film?

a. Spin coating
b. PECVD
c. Dip coating
d. Sputtering Deposition techniques

Photolithography

- Basic Photolithography process
  - UV exposure (dosage) changes the material properties of a photoresist layer
  - The sample is submerged in developer which removes the exposed (nonexposed) regions of the photoresist if it is positive (negative)
  - Etch step removes material in the desired pattern
  - Deposit top cladding

E-Beam Lithography

- Similar process to photolithography, only using an electron beam to spur reactions in the resist layer
- E-beam resist rather than photo resist (similar effects but through different chemical processes)
- Higher resolution (10nm vs 100 nm) at a much higher cost
- Lower Scalability than photolithography (larger, more complicated designs)

Zoom Poll 7

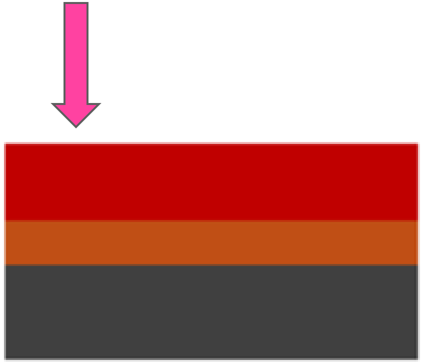
If you are trying to change the phase information of a photon in a thin film Lithium Niobate waveguide, what would you do?

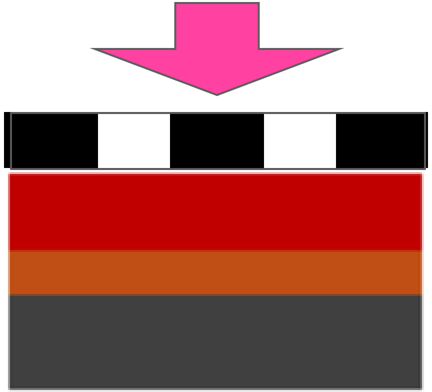
a. Deposit an ohmic heater to change the index by changing the temperature
b. Deposit an electrode over the desired region and apply an external E-field
c. Pump another laser on the region in the desired direction

Mask vs. Maskless

While E-Beam lithography does not require a mask, some photolithography applications require it.

- Very pricy and time consuming to fabricate
- Great resolution for high complexity architectures





Zoom Poll 8

You are making interconnects between two integrated circuits. Assuming these interconnects will be straight waveguides, and you do not have the proper photomask on hand. What is the proper lithography technique which minimizes time and costs (assuming you have the proper equipment)?

a. Create a photomask and use photolithography
b. Use a maskless lithography process
c. E-Beam lithography so that your resolution is maximized

Etching

- Step in which the target material layer is reduced to its desired thickness
- Dry: free radicals from gases react with substrate
- Wet: liquid etchants, high selectivity, larger throughput

	Wet Etch	Dry Etch
Profile		
Etchant	Chemical	Ionized Gas
Minimum Features	> 2µm	> Single nm
Selectivity	High > 100x	Low < 10x
Throughput	High (Batch)	Low (Single Wafer)

Hartensveld, Matthew. (2018). Optimization of Dry and Wet GaN Etching to Form High Aspect Ratio Nanowires. 10.13140/RG.2.2.19319.11687.

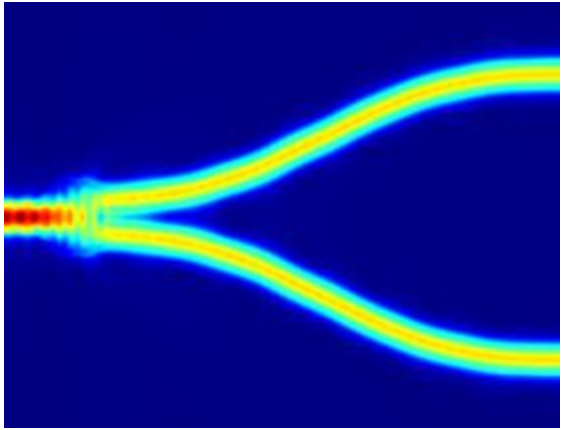
Zoom Poll 9

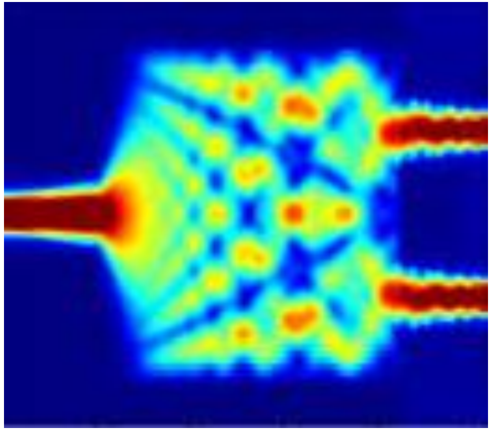
What type of lithography process would you use to make a photonic crystal lattice?

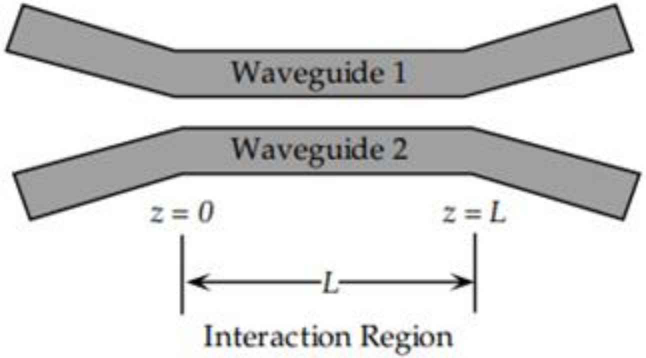
a. Maskless photolithography
b. Electron Beam Lithography

50/50 splitter

- Y-branch
- Multimode Interference Coupler (MMI)
- Directional Coupler



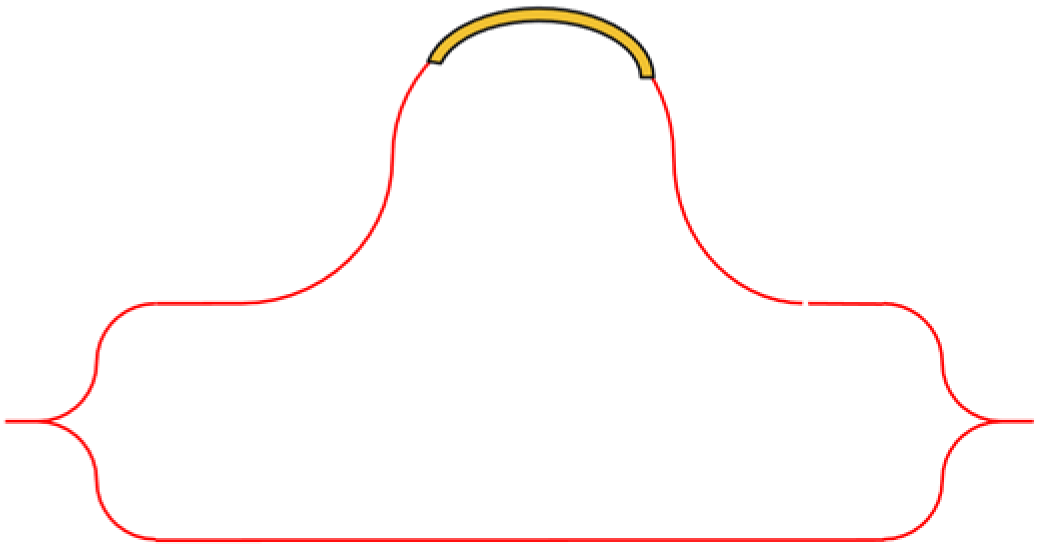




Ansys

Mach-Zehnder Interferometer (MZI)

- Intensity modulation
- Optical Switching
- Filtering
- Path Encoding



Zoom Poll 10

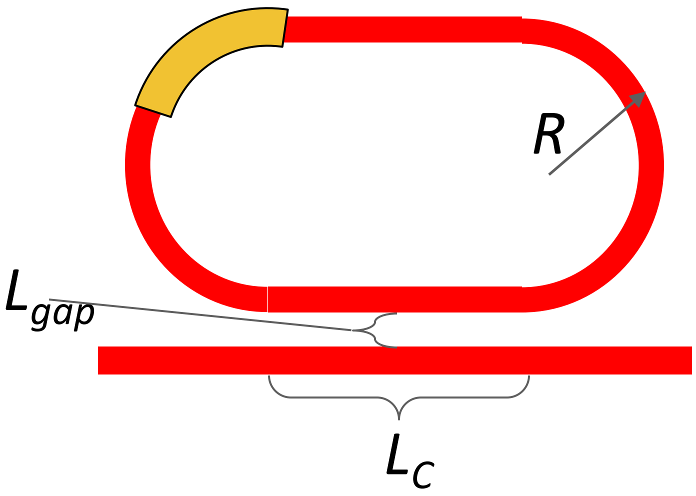
After top cladding is placed on a photonic integrated circuit (PIC), you want to place an electrode for a phase modulator on one branch of an MZI. You have already deposited and patterned the desired electrode dimensions. What process should you use for depositing the metal layer required?

a. Spin coat the molten metal on the wafer
b. Use PECVD to ensure an even layer
c. Sputter the proper metals over the wafer

Ring Resonators

- Maximize Q factor
  - Radius
  - Gap
  - Coupling region

- Critical coupling
  - Light is does not re-couple back into the bus waveguide



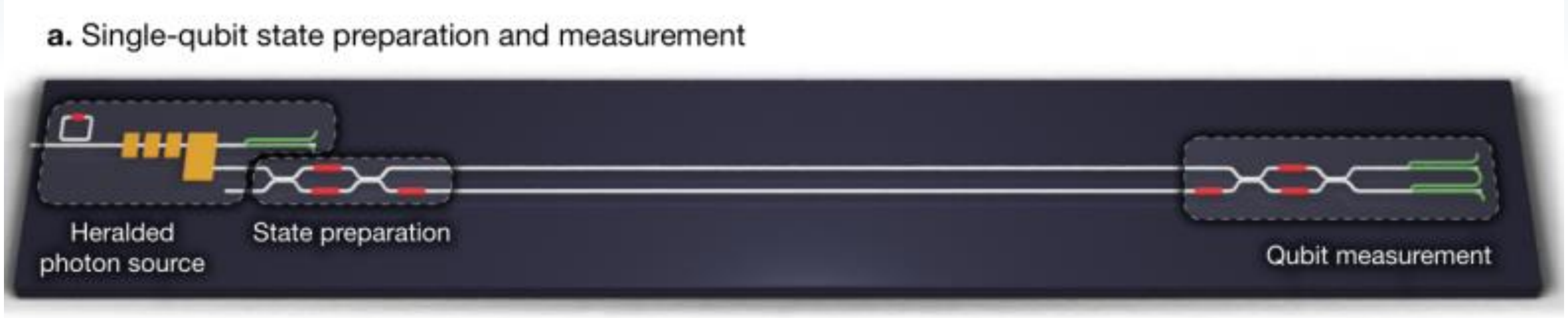
$Q = \nu_{res} / \Delta\nu$ $\quad$ $F = FSR / \Delta\nu$

Zoom Poll 11

Why are ring resonators good candidates for nonlinear EPR sources?

a. For a chosen coupling region, pump photons can propagate over a long enough distance such that generated photons can appear
b. It is only good for second order materials due to the larger intensity of their EPR pairs
c. They are not good for EPR pair generation: too much power is lost no matter the dimensions

Full System



- Ring Resonator generates EPR-pairs, then heralded through BSM
- Filter systems: MZI's and Rings filter the pump
- MZI's are optimized to path encode heralded photons

"A manufacturable platform for photonic quantum computing." *Nature* 641, no. 8064 (2025): 876-883.

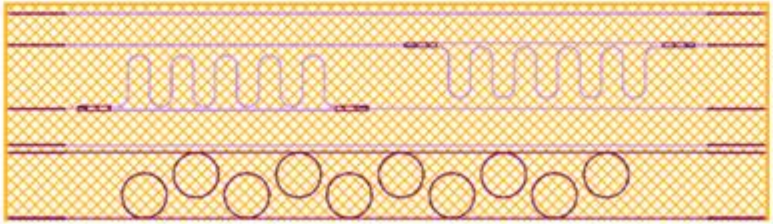
Zoom Poll 12

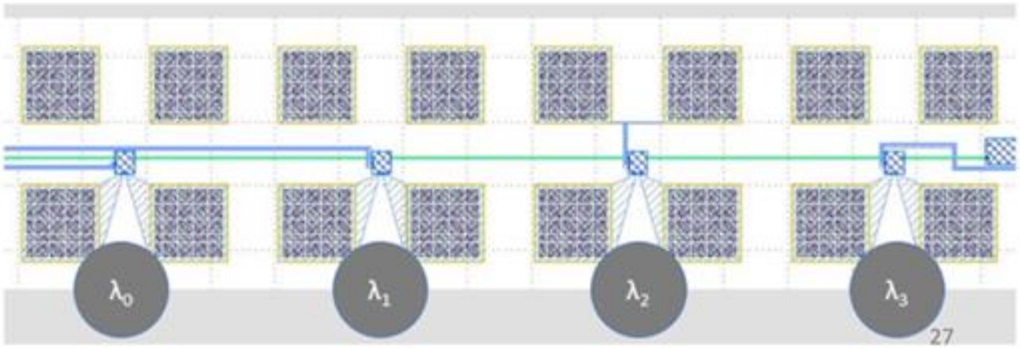
You have a ring resonator made from a material with high third order nonlinearity and no second order nonlinearity. The bus waveguide is already optimized for the pump wavelength. What should you do in order to maximize the Q-factor without fabricating a new device?

a. Place electrodes on some region of the ring and apply an external electric field
b. Deposit a Titanium-Gold layer as an ohmic heater
c. Place the entire device on a Peltier device to heat up the ring and bus waveguide
d. Apply a strain to the resonator

Foundries

- Sandia National Labs
  - Micro/nano fabrication
  - Nanostructure/semiconductor component synthesis
- AIM
  - Active/passive MPW
  - Silicon and Silicon Nitride based
- Ligentech
  - Active and passive Silicon Nitride based PICs





Conclusion

1. Motivations behind Quantum networks and EPR pair distribution
2. Basics of Waveguide functions, materials and geometries
3. Integrated photonic device fabrication
4. Applications on integrated photonics in quantum networks

Questions?

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Thank you!

- Wyatt Wallis, co-instructor
- Narayanan Rengaswamy, and Mike Raymer
- Center for Quantum Networks
- Brianna Moreno
- Noel Hennessey
- Belicia Lynch
- Jessica Wysong