Center for Quantum Networks
NSF Engineering Research Center

How to build a quantum network: Hardware Perspective Part 1: Overview

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About this course

- Introduction to quantum networks from a hardware perspective

Part 1: **Context:** What hardware is needed for a quantum network and why.

Part 2: **Hardware:** A basic introduction to each hardware component.

This course will not include detailed theoretical descriptions of quantum hardware, It will serve to introduce those unfamiliar with quantum networks to the basics.

"Never underestimate the joy people derive from hearing something they already know"
--Enrico Fermi

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Course	Level	Instructors	Scheduled Time (AZ/MST)
Physics behind quantum networks: A gentle introduction	1, 2	Dr. Michael Raymer and Abby Gookin	Jan 2, 1:00 PM – 4:30 PM
Optical networks for quantum networks	1, 2	Dr. Dan Kilper and Dr. Shelbi Jenkins	Jan 3, 9:00 AM – 12:30 PM
How to build a quantum network/ Hardware perspective	1,2,3	Dr. Ryan Camacho and Ian Briggs	Jan 3, 1:00 PM – 4:30 PM
How to build a quantum network/ Theory perspective	2	Dr. Don Towsley and Matheus Guedes de Andrade	Jan 4, 9:00 AM – 12:30 PM
Theory of quantum channels for quantum networks	3, 4	Dr. Quntao Zhuang and Dr. Anthony J. Brady	Jan 4, 1:00 PM – 4:30 PM
Information in a photon	2, 3	Dr. Saikat Guha and Dr. Christos Gagatsos	Jan 5, 9:00 AM – 12:30 PM
Classical and quantum error correction	2	Dr. Bane Vasic and Dr. Narayanan Rengaswamy	Jan 5, 1:00 PM – 4:30 PM
Software for modelling quantum networks	2, 3	Dr. Ines Montano and Jaime Diaz	Jan 6, 9:00 AM – 12:30 PM
Programmable photonics in quantum networks	2	Dr. Dirk Englund and CJ Xin	Jan 6, 1:00 PM – 4:30 PM

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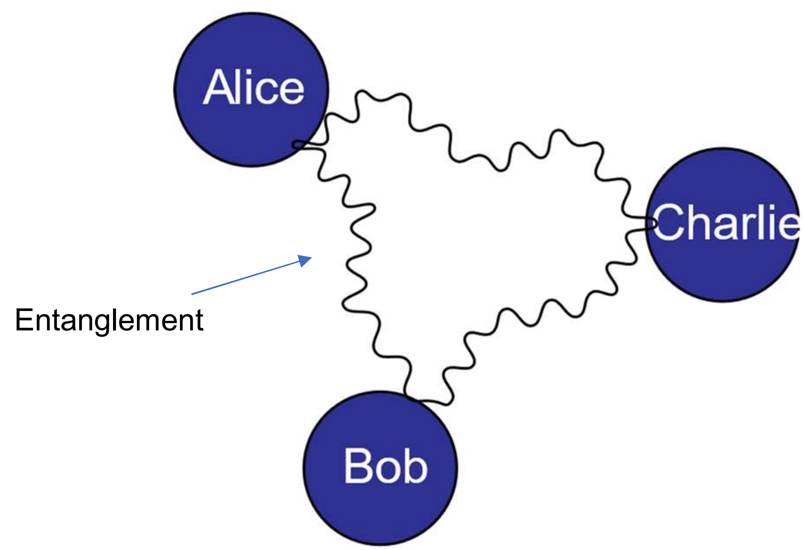
Part 1: Overview (60 minutes)

In this section, we will answer the following questions:

1. How can we create and distribute entanglement using light–what hardware is required?
2. What does the hardware need to do?



Introduction: What are quantum networks?

Quantum networks use quantum correlations

Ok, but what are quantum correlations?

Let’s play a game…

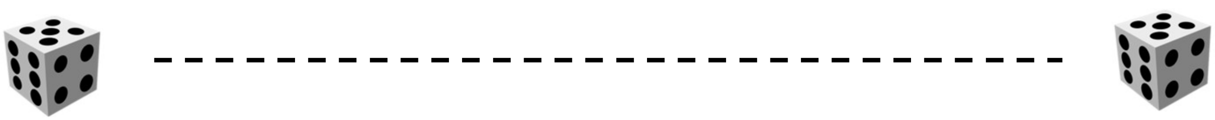
Prisoner's coordination

Alice and Bob need a shared alibi, but didn't have time to decide which one to use before they were captured.   If they don't tell the same story, they will be found guilty.

Alice

Bob

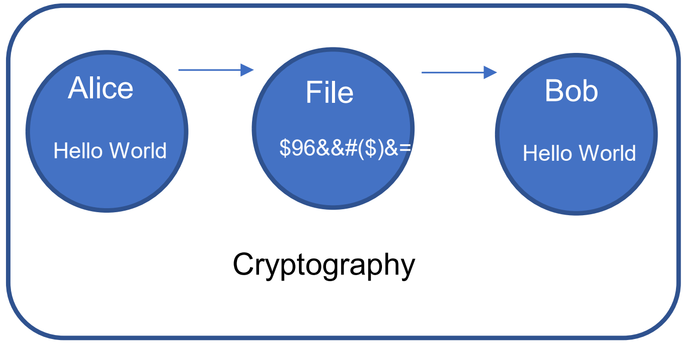
Luckily, they share a pair of magic dice!



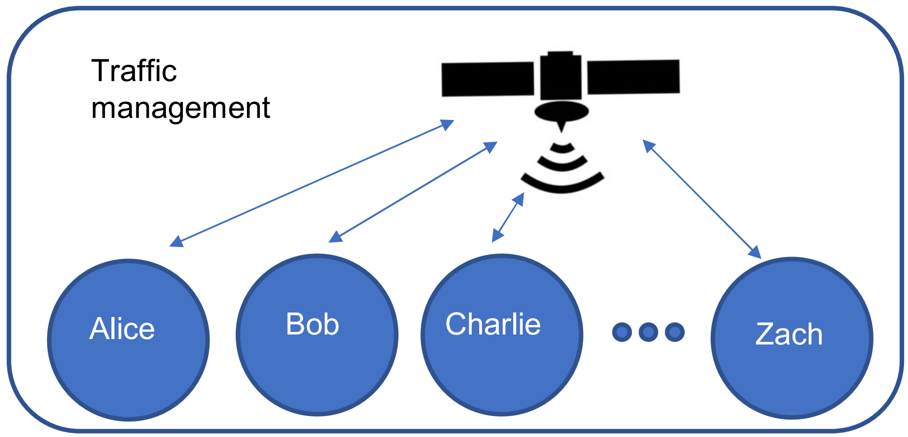
Where else would magic dice be useful?

ATCA telescope (Australia)

Telescope arrays need to share the same phase.



Alice and Bob need a shared key

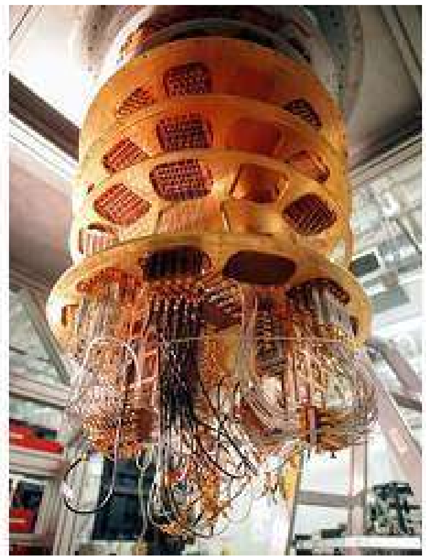


Dynamic coordination of senders/receivers

Distributed quantum computing

Beowulf Cluster

“…thirty men's heft of grasp in the gripe of his hand"



Google’s quantum computer

So how do I make magic dice?

We first need to understand **three aspects** of quantum mechanics *not* present in classical mechanics:

1. Quantum Superposition

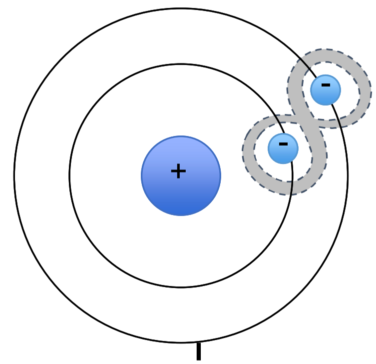
An object can simultaneously be in a superposition of more than one “state”.

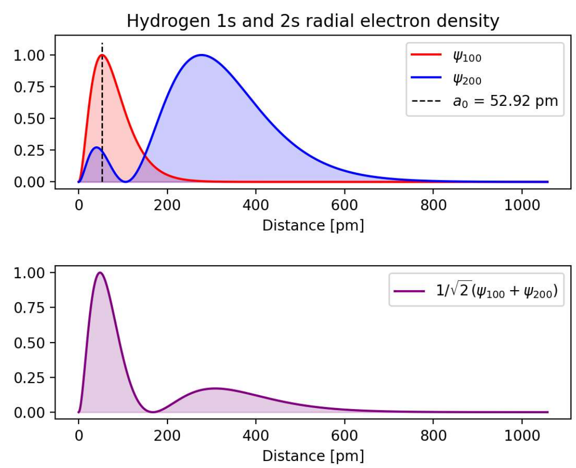
2. Quantum Entanglement

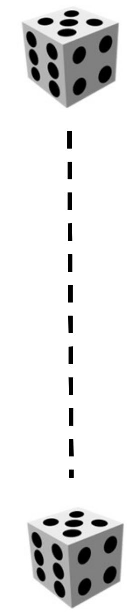
Multiple objects’ superposition states can be correlated.

3. Wave-function Collapse

If you measure the state of an object, its quantum superposition collapses to just one state.



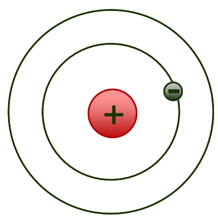




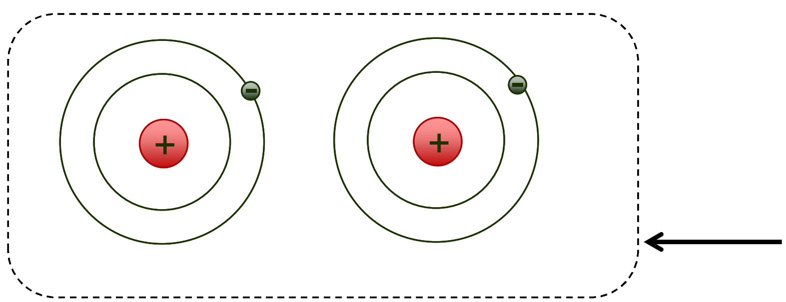
Magic Dice!

DIY: How to make magic dice in 5 easy steps

Step 1: Choose a quantum object—preferably one that has discrete states. (e.g. an atom, photon, electron, nucleus, Josephson junction, quantum dot, etc). If you're following along at home, for the rest of this tutorial we'll use single-electron atoms, a common item in most households.



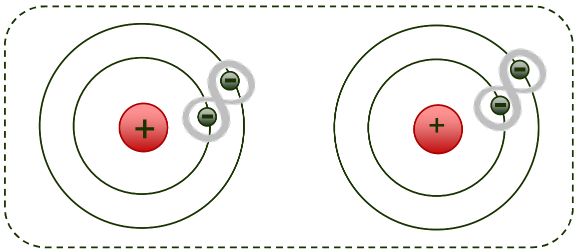
Step 2: Prepare two atoms in an excited state and put them inside a dark box. Note: the box should be able to detect when a single photon hits it from the inside (see step 3).



Hint: If you can't find a single photon detector box at your local hardware store, you may have to make your own

DIY: How to make magic dice

Step 3: Wait for one of the atoms to decay. If you're impatient you can send in a single photon to trigger a stimulated emission event. Tip: you'll know an atom decays when your box detects a photon, but you won't know which atom!



Step 4: Take both atoms out of the box and send one to a friend *without disturbing it*.

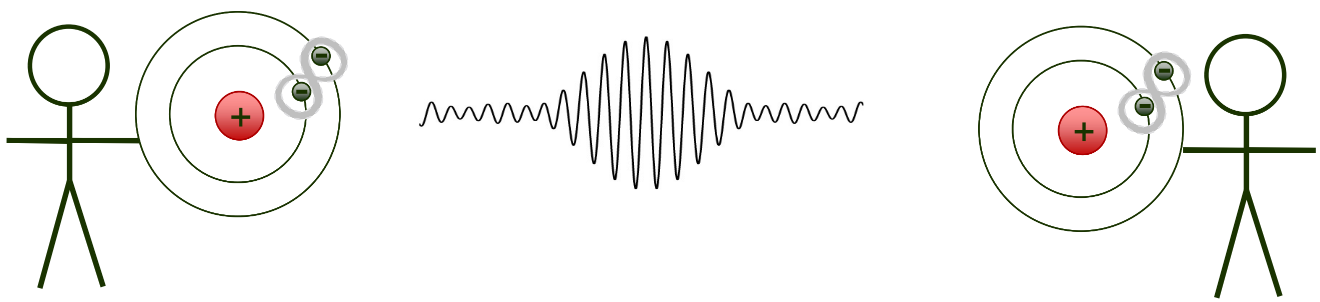
Step 5: Measure the state of your atom. If your magic dice are working properly, your friend should measure the opposite state from you every time you repeat steps 1-5.

A few (im)practical issues with our quantum object

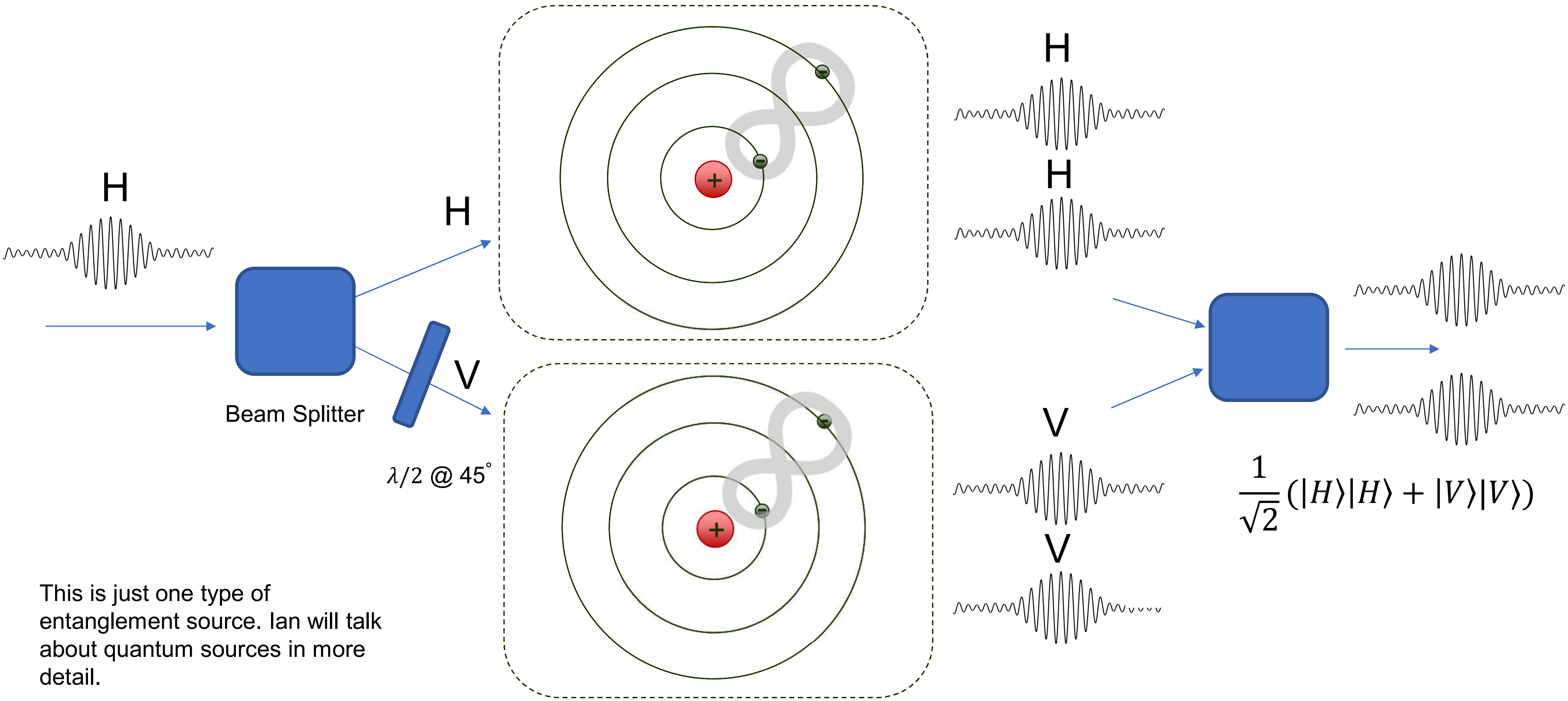
1. Single atoms are hard to control. Can we get a better atom please?
2. Single photon detectors are hard to make. But they are getting better!
3. **Sending a single atom in a quantum superposition state over a long distance without disturbing it is *really* hard.**

photonspot.com

Much better to convert entangled atomic superpositions to entangled photon superpositions and send the photons!



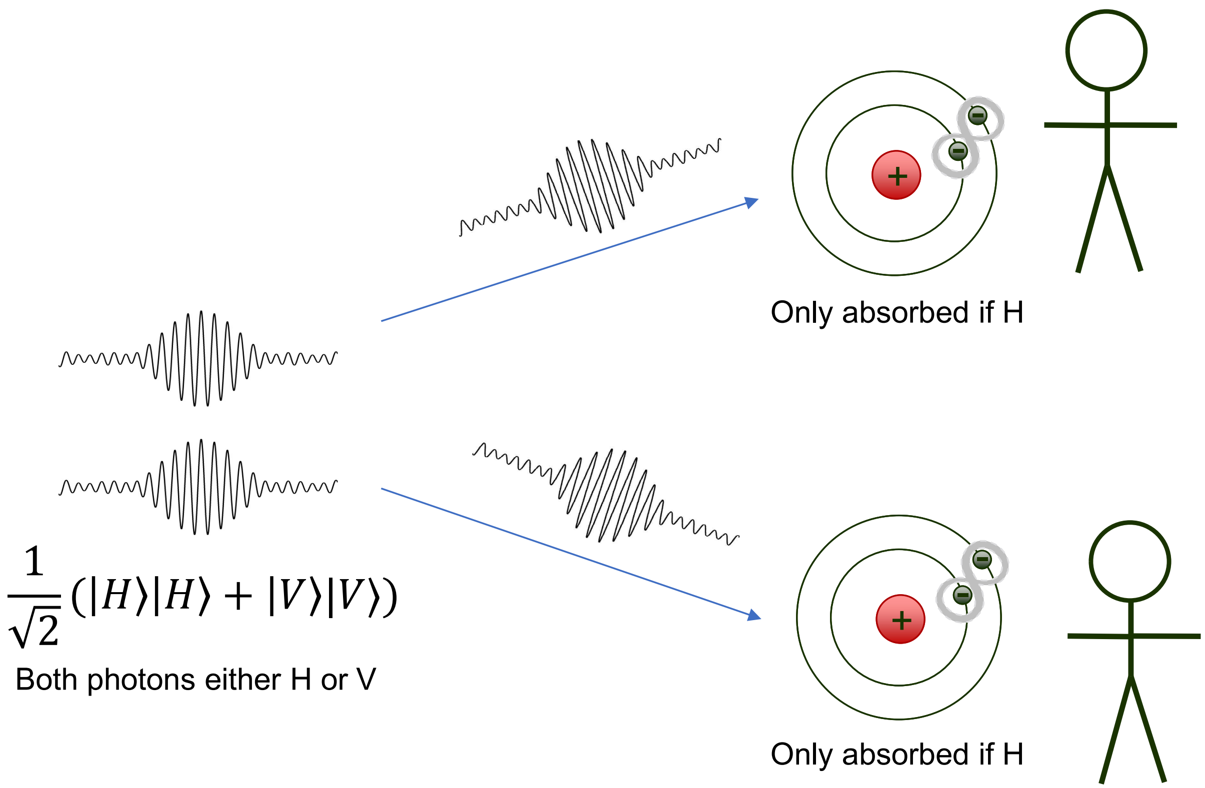
Entangled Photons



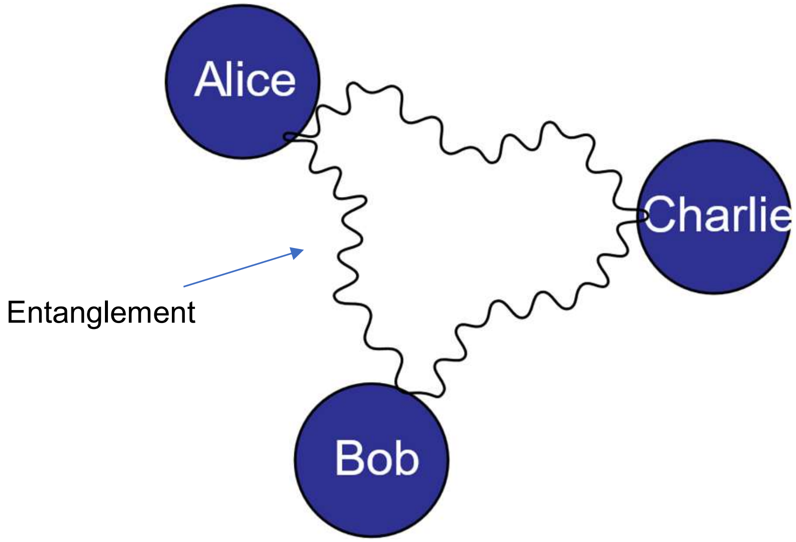
$$\frac{1}{\sqrt{2}}(|H\rangle|H\rangle + |V\rangle|V\rangle)$$

This is just one type of entanglement source. Ian will talk about quantum sources in more detail.

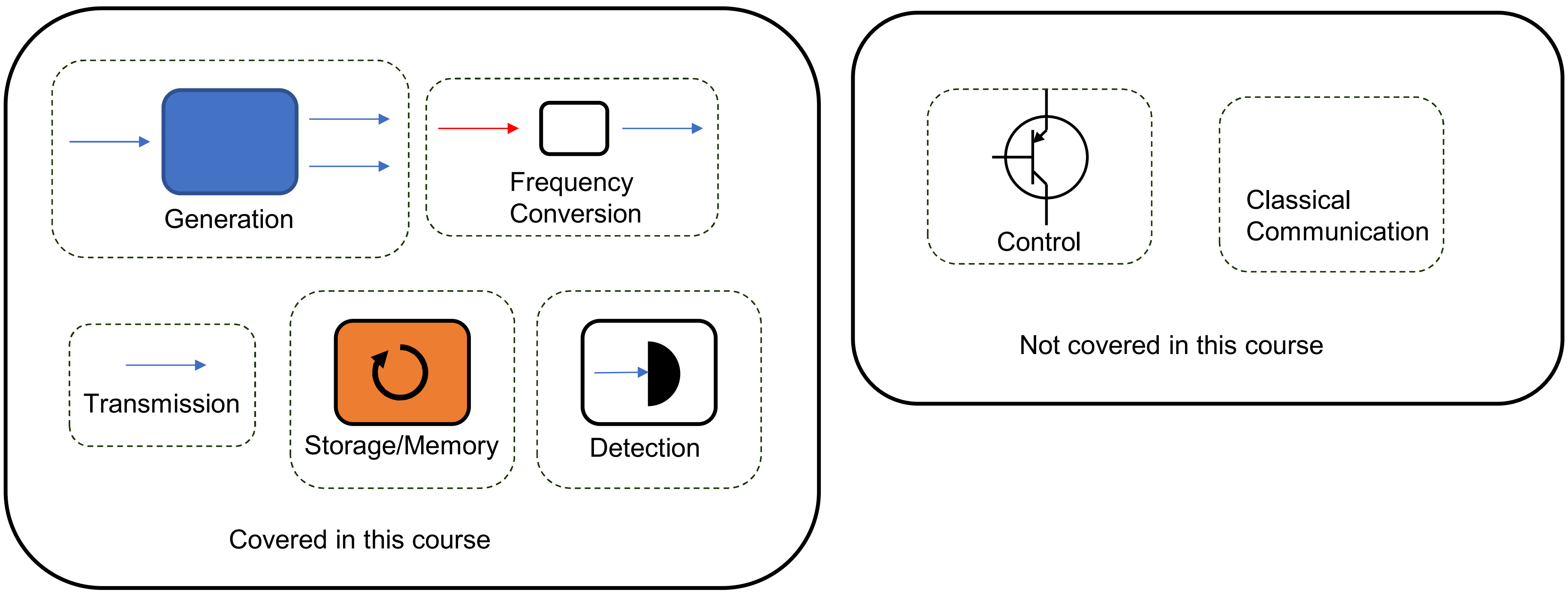
Distribute Entanglement



Use many entangled photons to create a network of correlations



Hardware to build a quantum network



What types of quantum networks are there?

Answer: Many! Different quantum states, topologies, protocols, etc.

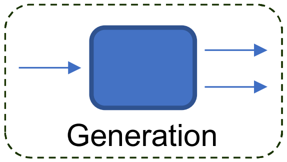
- DV vs CV
- Quantum States / Photonic Degrees of Freedom

Discrete Variable

Continuous Variable

Gaussian vs non-Gaussian modes

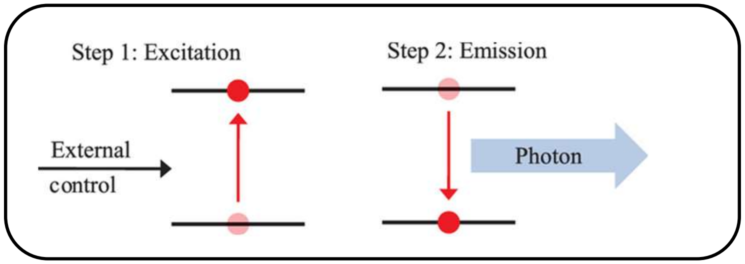
Gaussian vs non-Gaussian functions



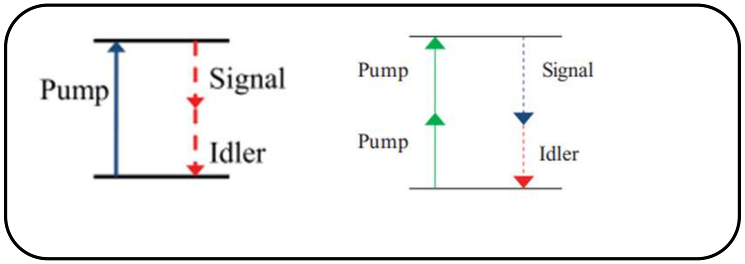
Hardware Introduction: Quantum Sources

Key concepts:

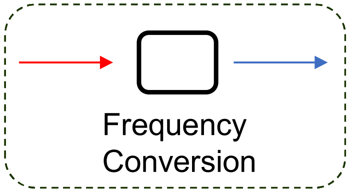
- What atomic systems can be used as sources?
- How to control nonlinearities and achieve phase matching?
- How to characterize source using fidelity, indistiguishability, efficiency
- How to use cavities to enhance atom-photon interaction strength?
- How to create entanglement sources from single photons?
- Bonus: How to create continuous variable entanglement using squeezed light



Single photon sources



Bi-photon sources



Hardware Introduction: Quantum Frequency Conversion

Key concepts:

- Creating and storing quantum information is most efficient at very low (RF) or very high (visible) frequencies
- Transmitting quantum information is efficient at infrared frequencies (~1.55 μm)
- What hardware is required to do quantum frequency conversion?
- How do noise and bandwidth affect quantum frequency conversion?

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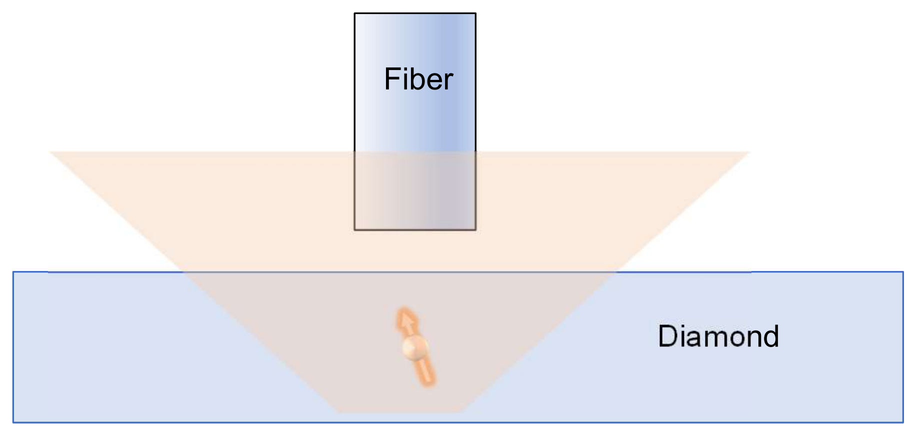
Transmission

Hardware Introduction: Quantum Transmission

Key concepts:

- No amplifiers allowed!
- Free-space vs waveguides
- What considerations should we consider when building our transmission channel?
- The importance of the photon-matter interface



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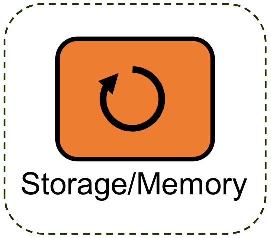
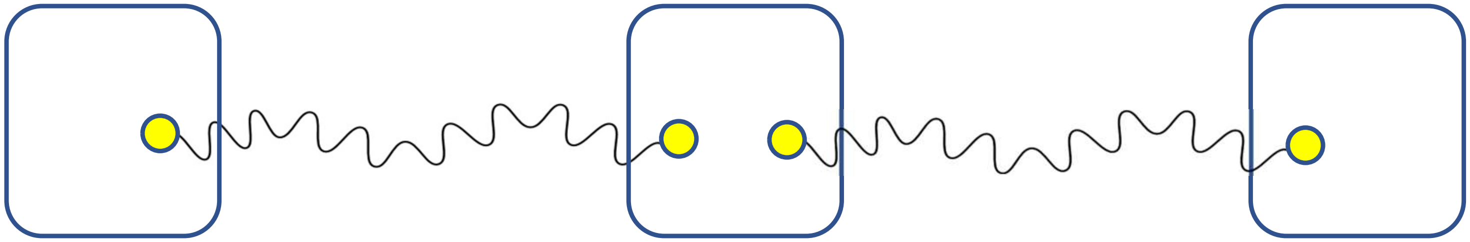
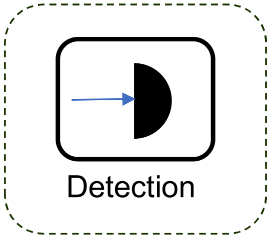


Hardware Introduction: Quantum Memories

Key concepts:

- Memories required for practical two-party and multi-party entanglement
- Quantum teleportation as the basis for extending entanglement
- What types of quantum memory are being explored?
- The importance of cavity enhancement



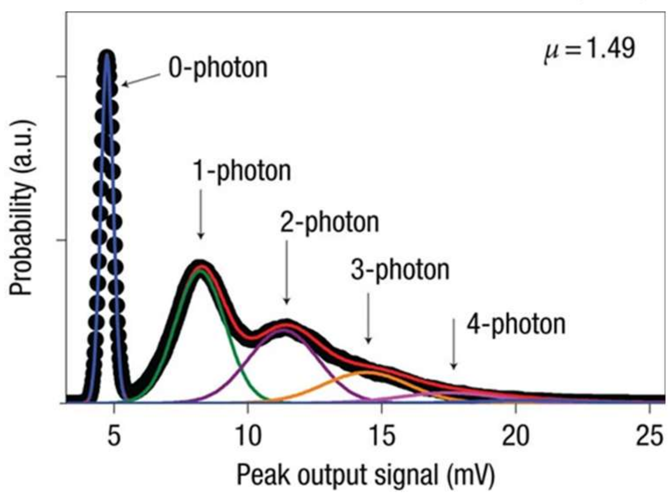


Hardware Introduction: Quantum Detection

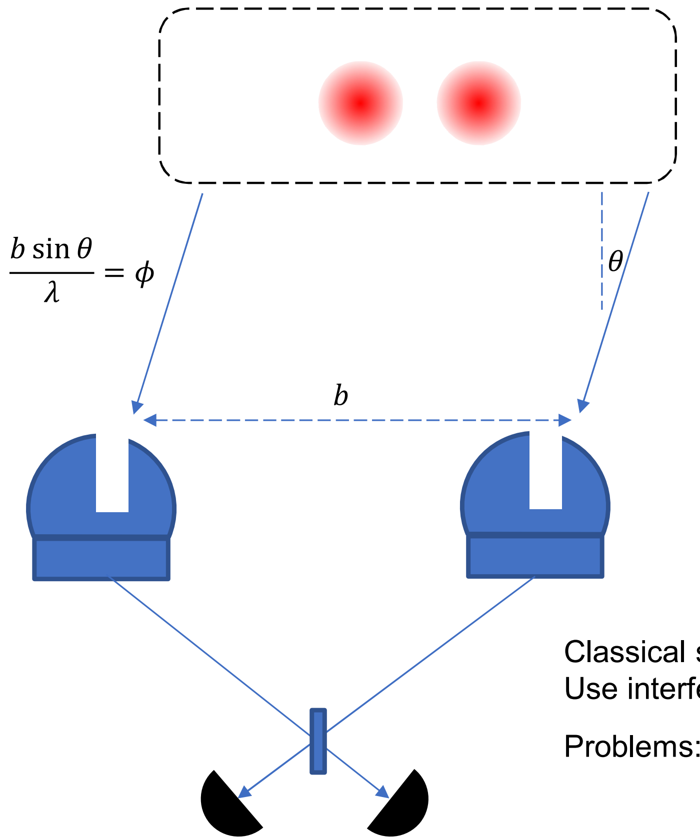
Key concepts:

- What are the different types of quantum detectors (avalanche, superconducting, etc..)?
- Photon number resolving detectors
- How can we compare the performance of quantum detectors?

Nat Phot 2, 425-428 (2008)



Application Example: Quantum Telescope



State of single photon coming from distant object

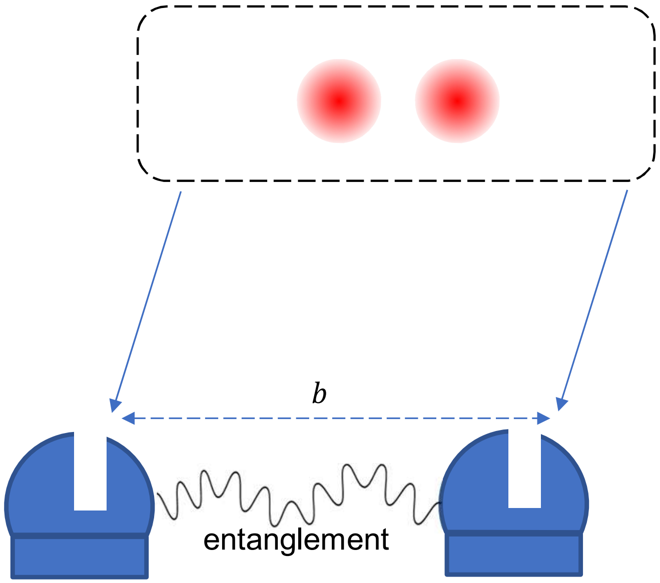
$$|0\rangle_L|1\rangle_R + e^{i\phi}|1\rangle_L|0\rangle_R$$

Determing ϕ can precisely locate object

Classical solution: **Direct Detection**
Use interference to find ϕ

Problems: Loss + phase noise limits baseline distance b

Daniel Gottesman, Thomas Jennewein, and Sarah Croke
Phys. Rev. Lett. **109**, 070503



Quantum Solution: **Entanglement-based phase measurement**
Use Bell-state measurement to find ϕ

Problems: Need a quantum network!

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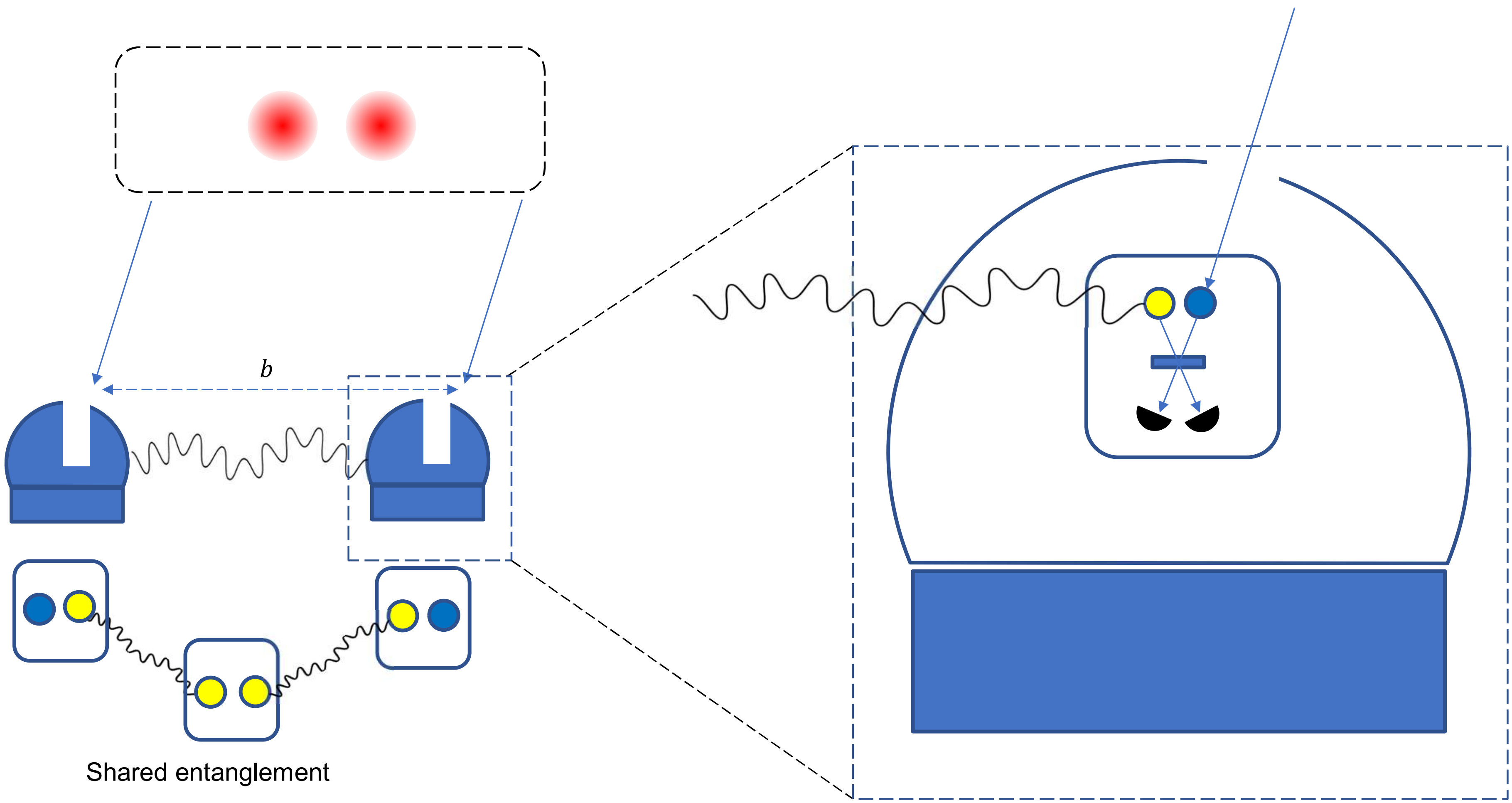

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How to build a quantum network: Hardware Perspective
Part 2: Hardware

Instructor: Ryan Camacho
Brigham Young University
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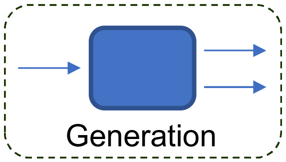
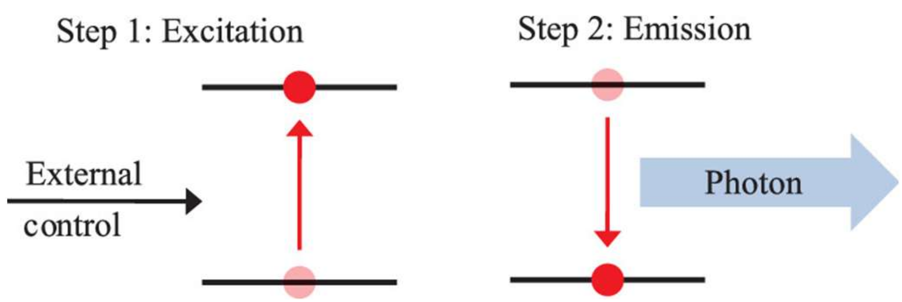
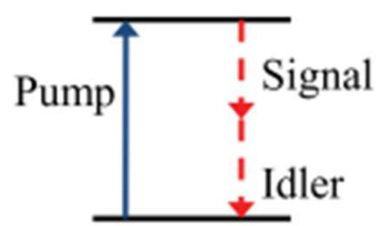
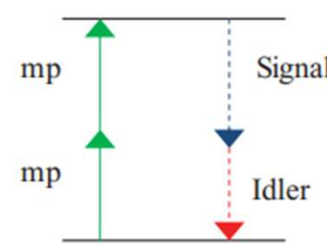


Photonic Quantum Sources

- Need a state of light in which quantum behavior is readily apparent
- Single photon sources: single photon in single mode
  - Attenuated laser light: relatively simple, don’t see characteristic photon anti-bunching statistics need for quantum applications
  - Fluorescence from atomic systems: on-demand sources, requires trapping and cooling, some problems with distinguishability
  - Spontaneous nonlinear processes: high emission rates, indistinguishable, compatibility with integrated photonics, heralded single photon emitters







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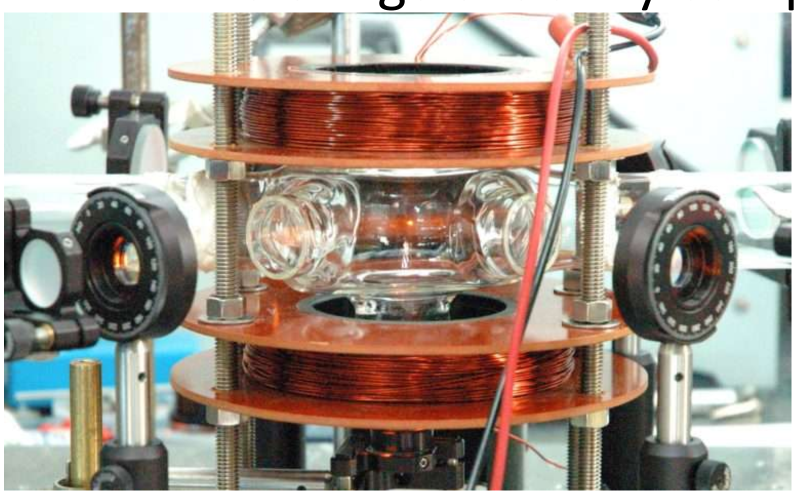
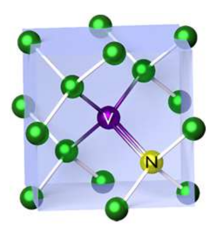
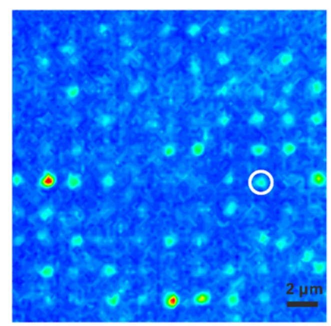
atomic systems

- Trapped atoms/ions/molecules, quantum dots, defect color center,...
- external control used to put system in excited state, photon emitted upon relaxation to lower-level state
- atomic systems can act as deterministic photon sources, can achieve high brightness and fidelity
- Trapping single atoms/molecules requires bulky setup (MOT)
- indistinguishability compromised by environment/charging effects

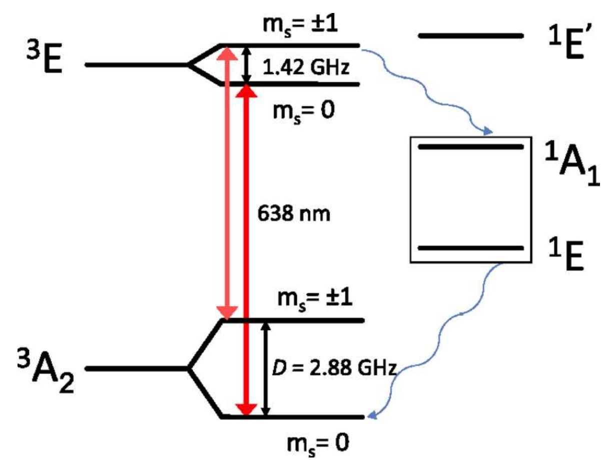


https://www.findlight.net/blog/magneto-optical-traps-laser-cooling/





Phys. Rev. Lett. **124**, 223601



Phys. Rev. B **90**, 235205

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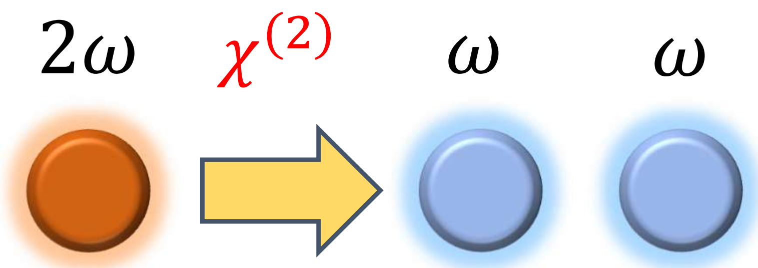
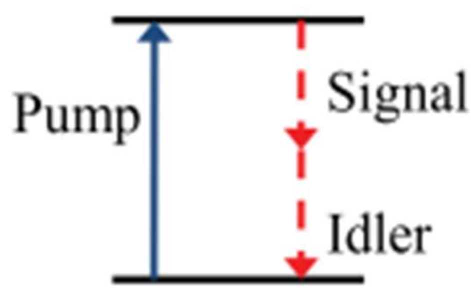
Nonlinear sources

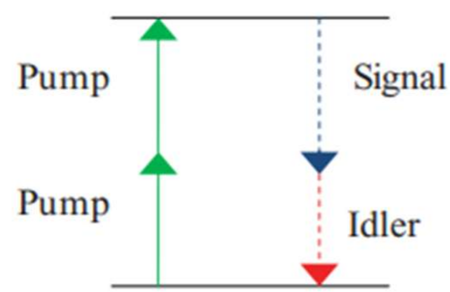
- Spontaneous photon pair source: one photon heralds another
- Stems from taylor expansion of electric susceptibility

$$P = \varepsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \cdots)$$

- Used to convert photons from one frequency to another, as long as energy and momentum is conserved
- $\chi^{(2)}$: spontaneous parametric down conversion (SPDC)
- $\chi^{(3)}$: spontaneous four-wave mixing (SFWM)





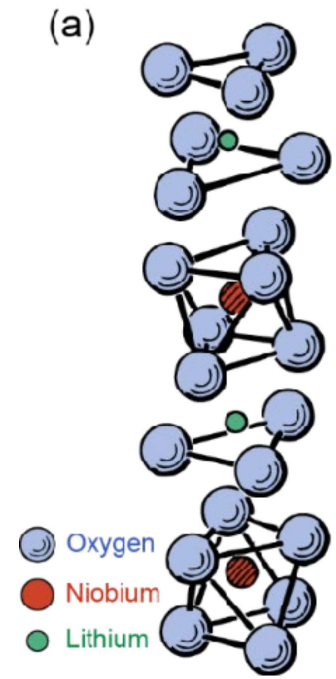


2nd order nonlinearity

- Not every material has $\chi^{(2)}$, but $\chi^{(2)}$ nonlinearity tends to be much stronger than $\chi^{(3)}$ in materials that have $\chi^{(2)}$
- $\chi^{(2)}$ emerges in anisotropic geometry in crystal
- Energy conservation: $\omega_3 = \omega_1 + \omega_2$
- Momentum conservation: $k_3 = k_1 + k_2$

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = 2 \times \begin{pmatrix} 0 & 0 & 0 & 0 & d_{31} & -d_{22} \\ -d_{22} & d_{22} & 0 & d_{31} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_zE_y \\ 2E_zE_x \\ 2E_xE_y \end{pmatrix}$$

https://covesion.com/en/resource/material-properties-of-lithium-niobate/



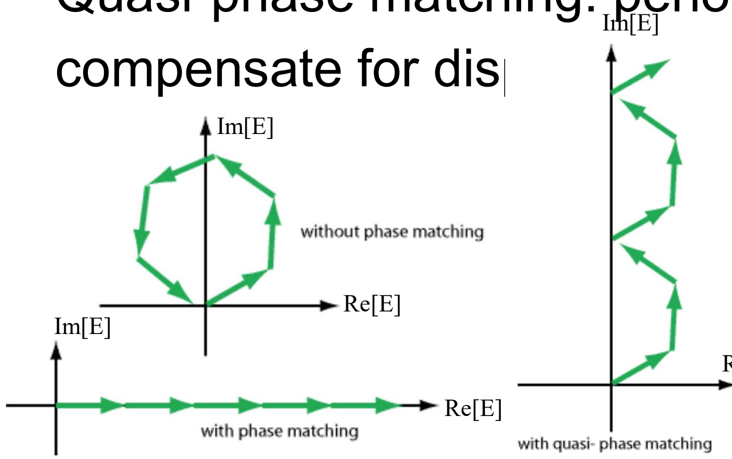
arXiv:2102.11956

Phase matching

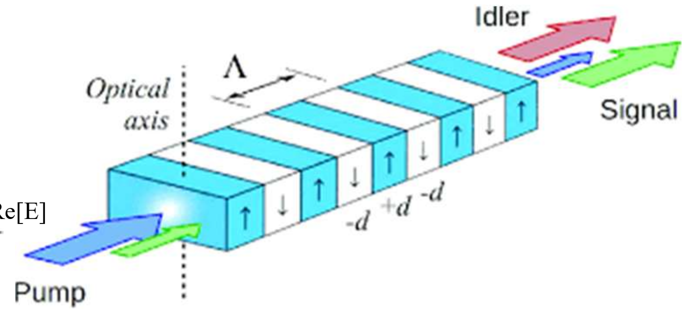
- Due to dispersion, photons at different frequencies travel at different speeds

$$\Delta k = k_s - 2k_f = \frac{2\omega}{c}(n_s - n_f) \neq 0$$

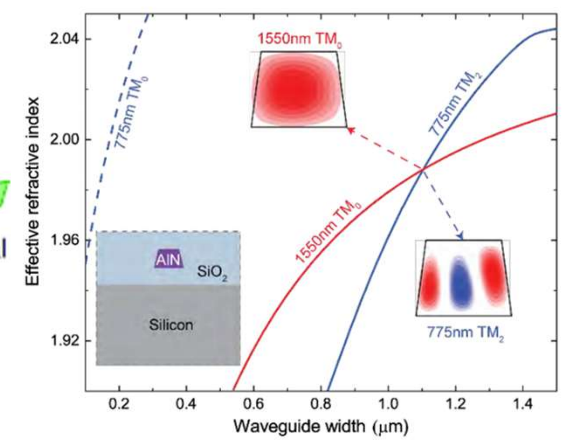
- Dispersion engineering: phase match fundamental spatial mode with higher order spatial mode
- Quasi-phase matching: periodically switch direction of crystal of compensate for dis $k = \frac{2\pi}{\Lambda}$



https://www.rp-photonics.com/phase_matching.html



C Manzoni and G Cerullo 2016 *J. Opt.* **18** 103501



Light Sci Appl 6, e16249 (2017)

What makes a Good Quantum Source?

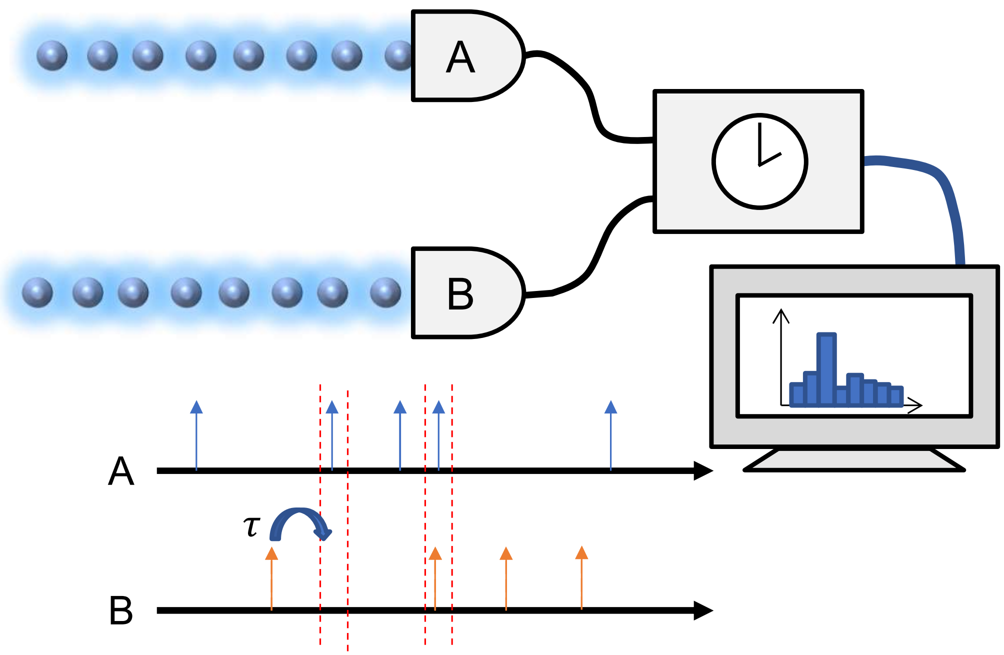
- Fidelity: how closely does the produced quantum state resemble the ideal quantum state?
- Indistinguishablility: are the produced photons identical in all degrees of freedom? Important for interferometric experiments
- Efficiency: what brightness can be achieved per pump power?

Coincidence Detections

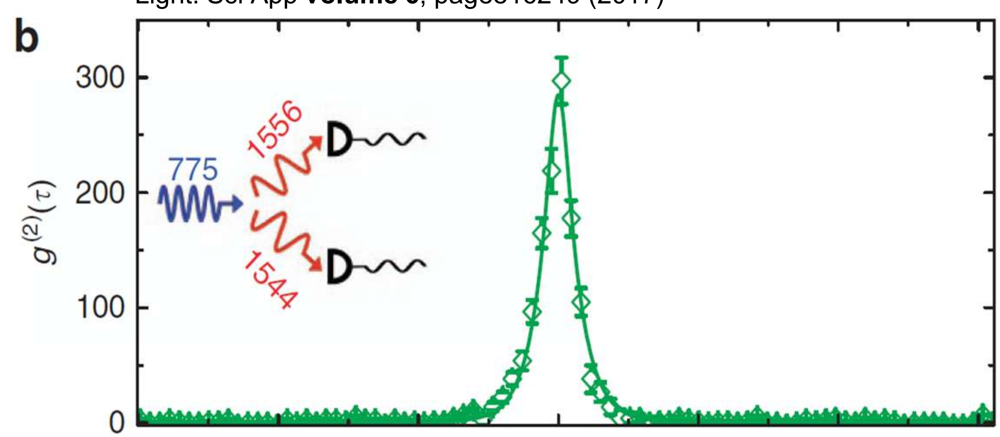
- Vital tool for characterizing single photon sources: second order correlation function

$$g_{(2)}(\tau) = \langle \hat{a}^{\dagger}(t)\hat{a}^{\dagger}(t+\tau)\hat{a}(t+\tau)\hat{a}(t)\rangle / \langle \hat{a}^{\dagger}(t)\hat{a}(t)\rangle$$

- Photon bunching: $g_{(2)}(0) > g_{(2)}(\tau)$, photon anti-bunching: $g_{(2)}(0) < g_{(2)}(\tau)$
- Experimentally, g2 is calculated using $g_{(2)} = \frac{R_{cc}}{R_1 R_2 \tau_b}$



Light: Sci App **volume 6**, pagee16249 (2017)



Purity

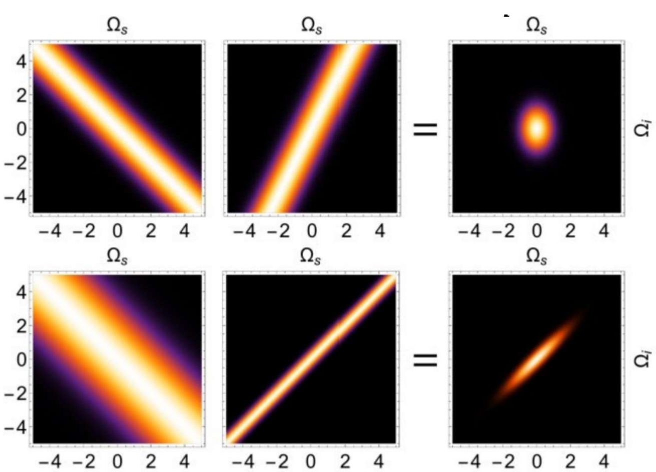
- Is the single photon in a single mode?
  - Self correlation function g(2) used to measure purity, use Hanburry-Brown Twiss interferometer
- Photon number: higher order emission
- Spectral: Schmidt mode decomposition

$$|\Psi\rangle = |1\ \text{photon}\rangle$$

$f(\omega_s,\omega_i) = \sum_k b_k q_k(\omega_s) r_k(\omega_i)$ $\quad P_s = \mathrm{Tr}[\rho_s^2] = \sum_k b_k^4 \leq 1$

Separable

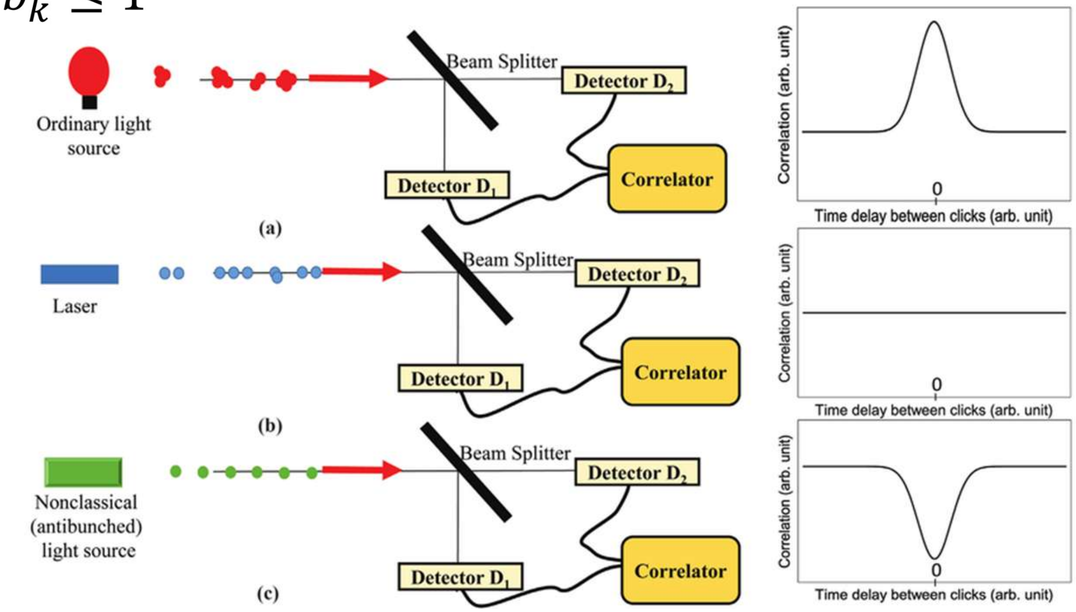
highly correlated



$\alpha(\omega_s+\omega_i)$ $\quad \phi(\omega_s,\omega_i)$ $\quad f(\omega_s,\omega_i)$

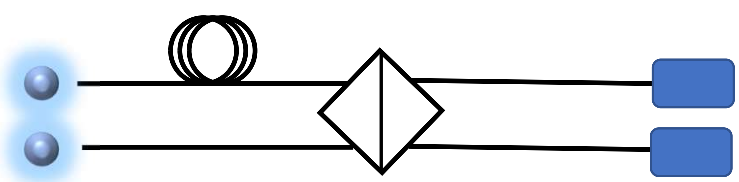
Phys. Rev. A **98**, 053811

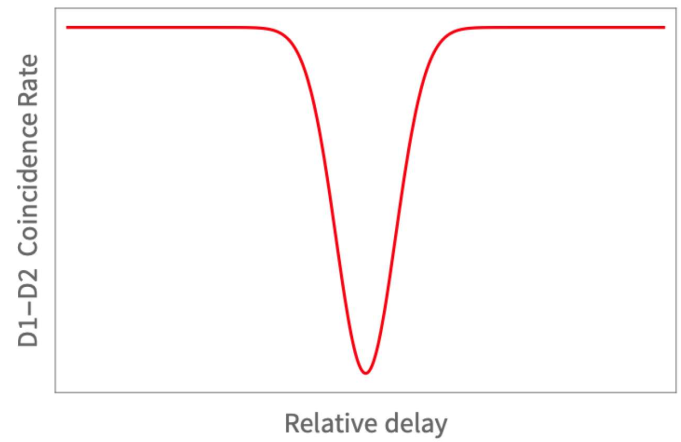
Light and its many wonders, Ch. 8, Ajoy Ghatak, 2015



Indistinguishability

- How similar are the photons?
  - Spectrum, time, polarization, space
- Provides upper limit for how well you can interfere photons
- Easier if comes from same source, need tuning mechanism for different sources
- Directly relates to visibility of HOM fringe

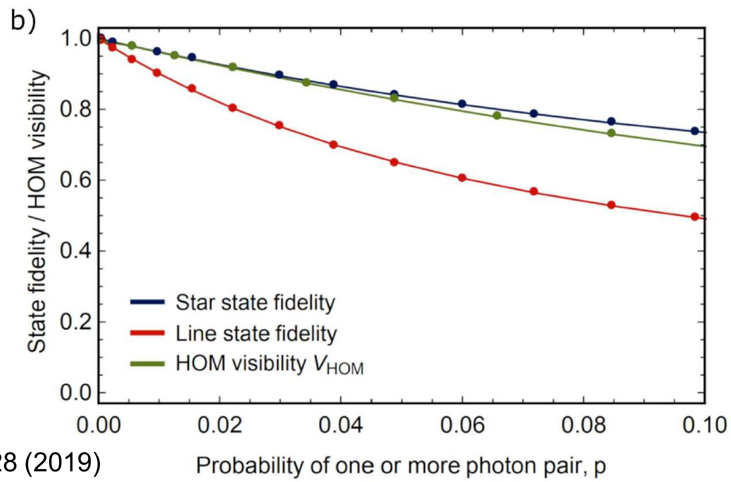




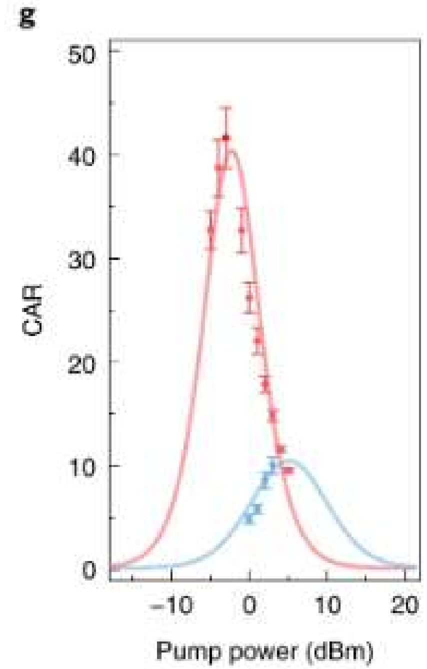
ArXiv:2005.07982

Brightness

- Different definitions depending on platform
  - Quantum dots: probability of emission per excitation event
  - Nonlinear sources: number of photons per unit pump power (squared, per unit bandwidth)
- Conversion efficiency, coupling efficiency, excitation efficiency,quantum efficiency, detector efficiency,…
- CAR: coincidence to accident ratio = $\max(g_{si}(t)) - 1$, 1 is background



Nat Comm **vol 10**, 3528 (2019)



Nat Phys, Vol 18, Iss 5, p.497-501

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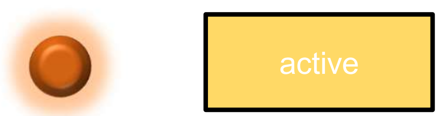
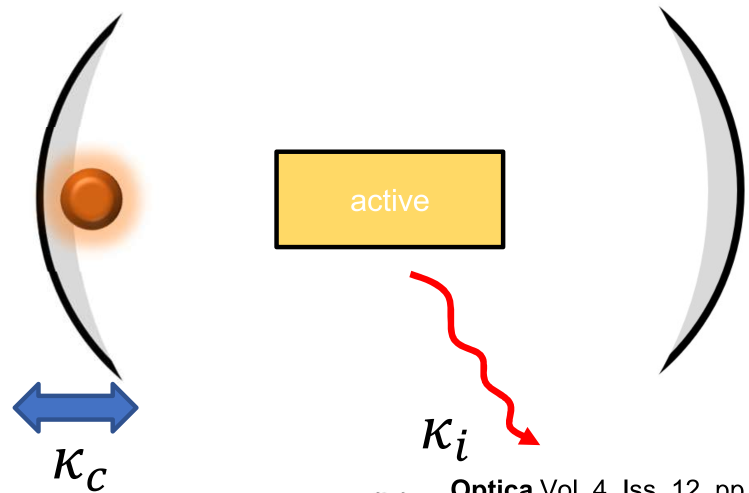
Cavity Enhancement

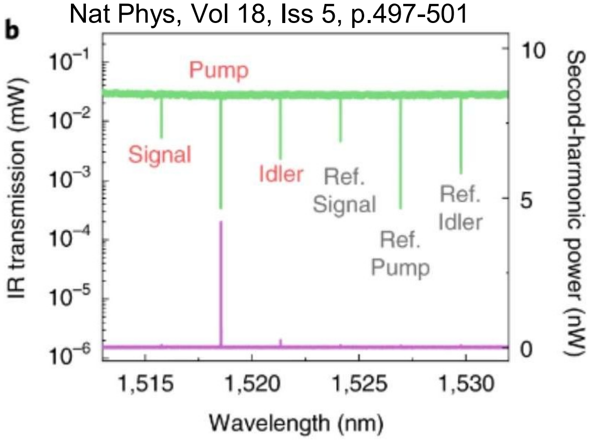
- Strength of many interactions can be enhanced using a resonator cavity



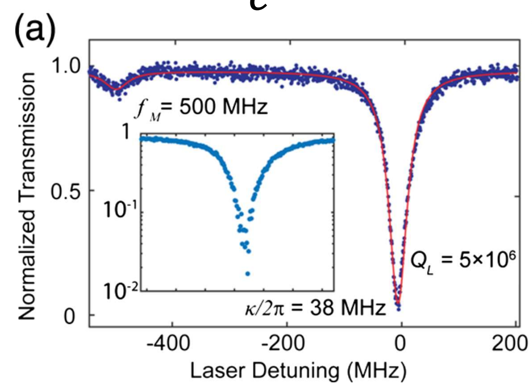


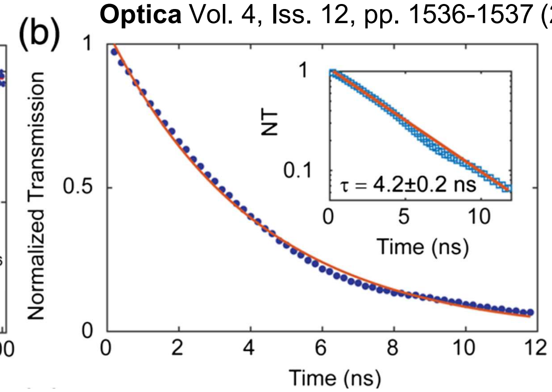
- $Q = 2\pi \dfrac{\text{energy stored}}{\text{energy dissipated per cycle}} = \dfrac{\omega}{\kappa}$
- Strength of interaction $\propto Q$ (Purcell factor)

Nat Phys, Vol 18, Iss 5, p.497-501



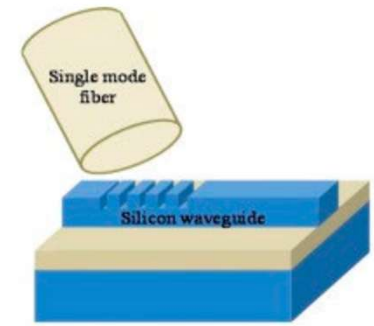
Optica Vol. 4, Iss. 12, pp. 1536-1537 (2017)



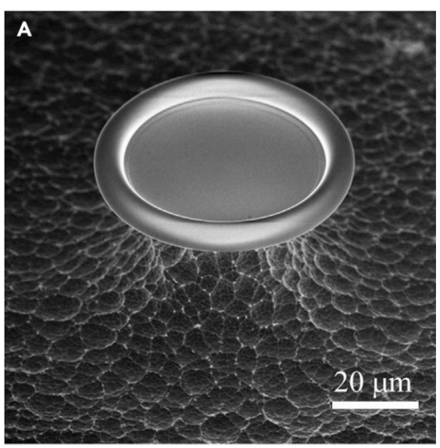


Nanophotonic vs free space

- Strength of nonlinear interaction, $g \propto 1/\sqrt{V}$
- Strong confinement -> strong interactions
- Fast modulation
- Coupling efficiency limitations

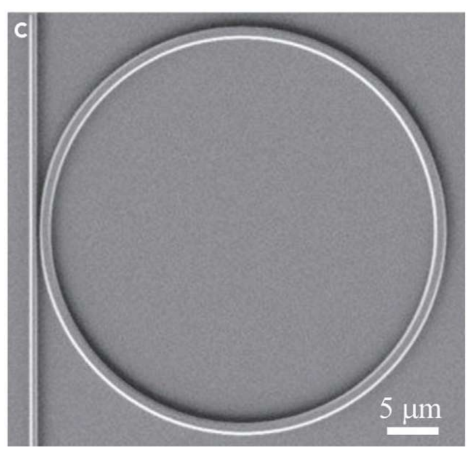


$Q > 10^8$

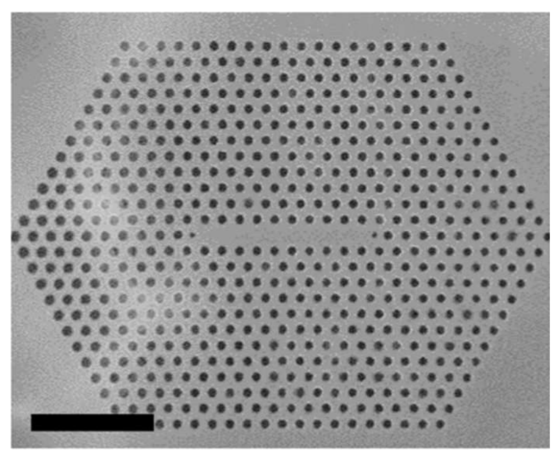


Matter. 2020 Aug 5; 3(2): 371–392

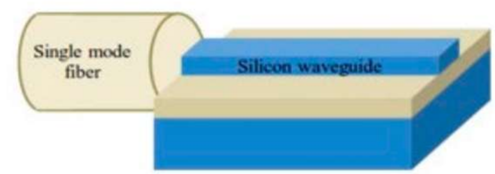
$Q \sim 10^6$



$Q \sim 10^5$



Nat Comm **9**, Article number: 2623 (2018)



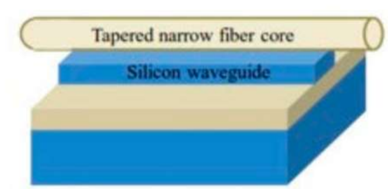
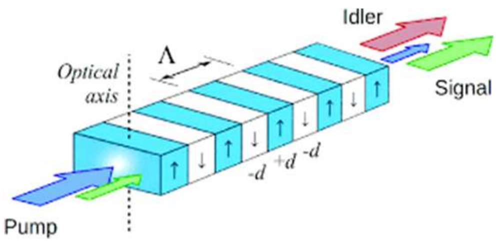


Photo and Nano – Fund & App 20 (2016) 41–58

Efficiencies

Single pass, waveguide:



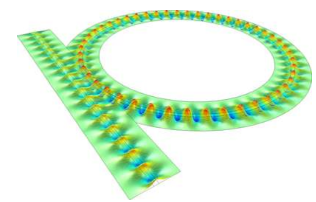
$$H_{NL} = -\int \mathrm{d}k_1 \mathrm{d}k_2 \mathrm{d}k S(k_1, k_2, k) a^{\dagger}_{Fk_1} a^{\dagger}_{Fk_2} a_{\mathrm{SH}k} + \mathrm{H.c.},$$

$$|\psi\rangle_{PDC} = |0\rangle - \frac{iAL}{h} \iint d\omega_s d\omega_i \, \alpha(\omega_s + \omega_i) \cdot \phi(\omega_s, \omega_i) \, \hat{a}_s^{\dagger}(\omega_s) \hat{a}_i^{\dagger}(\omega_i) |0\rangle$$

$$R_{SM}^{t1} = \sqrt{\frac{2}{\pi^3}} \frac{2}{3\epsilon_0 c^3} \frac{n_{g1} n_{g2}}{n_1^2 n_2^2 n_p} \frac{(d_{\mathrm{eff}})^2 \omega_p^2}{\sqrt{\kappa}} \times \left| \frac{\sigma_p^2}{\sigma_1^2 + 2\sigma_p^2} \right|^2 \frac{P}{\sigma_p^2} L_z^{3/2},$$

Bandwidth determined by phase-matching, pump profile, external filters

Resonator:



$$H = \omega_a a^{\dagger} a + \omega_b b^{\dagger} b + g[(a^{\dagger})^2 b + a^2 b^{\dagger}] + i\epsilon_s(-b e^{i\omega_s t} + b^{\dagger} e^{-i\omega_s t}).$$

$$b = \beta = \sqrt{\frac{2\kappa_{b1}}{\kappa_{b,tot}^2 + \delta_b^2}} \sqrt{\frac{P_s}{\hbar\omega_s}} e^{i\theta},$$

$$\frac{d}{dt} a = (-i\delta_a - \kappa_{a,tot}) a - i2g |\beta| a^{\dagger} - i\sqrt{2\kappa_{a,tot}} a_{in},$$

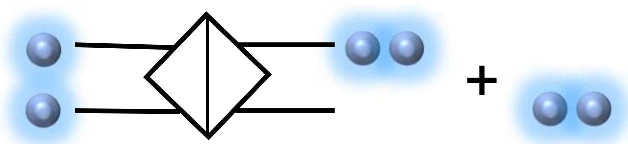
$$R = N_a/2 = \frac{2g^2 \kappa_{a,tot}}{\kappa_{a,tot}^2 + \delta_a^2} \frac{2\kappa_{b1}}{\kappa_{b,tot}^2 + \delta_b^2} \frac{P_s}{\hbar\omega_s}.$$

Bandwidth determined by linewidth of resonance
Brightness of output photon pairs also determined by coupling

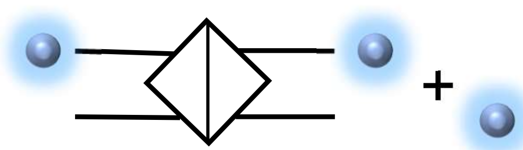
Entanglement generation

- Now that we have single photon sources, how do we create entanglement sources?
- Well, we have already seen one…

N00N state:



$|1\rangle_a|1\rangle_b$ $\qquad$ $\dfrac{|2\rangle_a|0\rangle_b + |0\rangle_a|2\rangle_b}{\sqrt{2}}$



$|1\rangle_a|0\rangle_b$ $\qquad$ $\dfrac{|1\rangle_a|0\rangle_b + |0\rangle_a|1\rangle_b}{\sqrt{2}}$

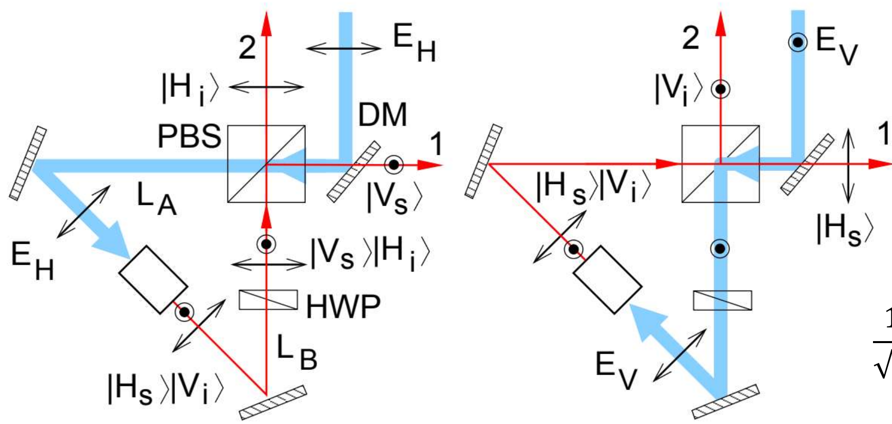
- Useful for quantum metrology: $\Delta\theta = 1/N$
- Generating N > 2 N00N states is challenging
- hard to construct local unitaries (single qubit operation) for state manipulation

$$\begin{pmatrix} \hat{c} \\ \hat{d} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix}$$

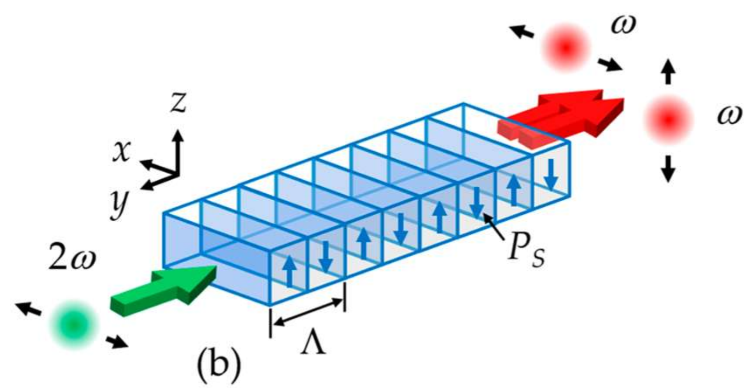
$$|1\rangle_a = \hat{a}^\dagger|0\rangle \Rightarrow \frac{1}{\sqrt{2}}\left(\hat{c}^\dagger + \hat{d}^\dagger\right)|0\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle_c + |1\rangle_d\right)$$

Polarization entanglement

- Polarization entangled photons created using type II SPDC
- Unitary transformations readily available using HWP,QWP
- Hard to manipulate polarization on integrated optics platform
- Have to compensate for polarization drift for fiber communication



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

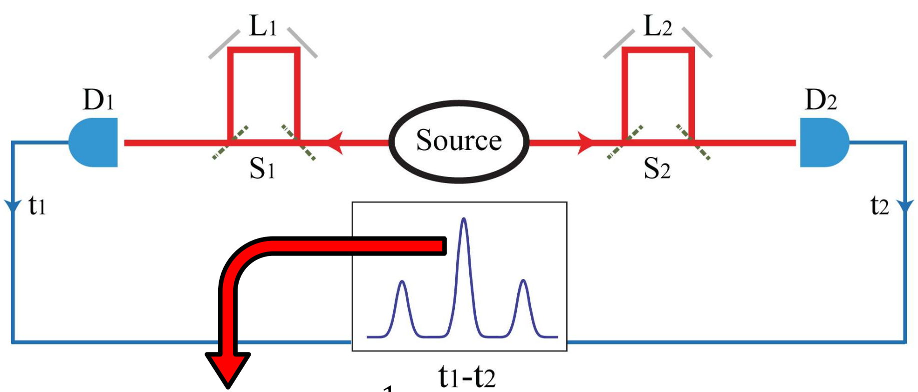


Phys. Rev. A **73**, 012316

Crystals **2021**, *11*(4), 406

Time bin entanglement

- Qbit encoded in terms of early and late arrival ($|S\rangle$, $|L\rangle$)
- Entanglement enabled via franson interferometer
- Need MZI of same length difference to enable local unitary operation
- Robust against decoherence



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|S\rangle_1|S\rangle_2 + e^{i\phi}|L\rangle_1|L\rangle_2)$$

Optics Express, Vol. 21, Iss. 21, p. 25492-25500 (2013)

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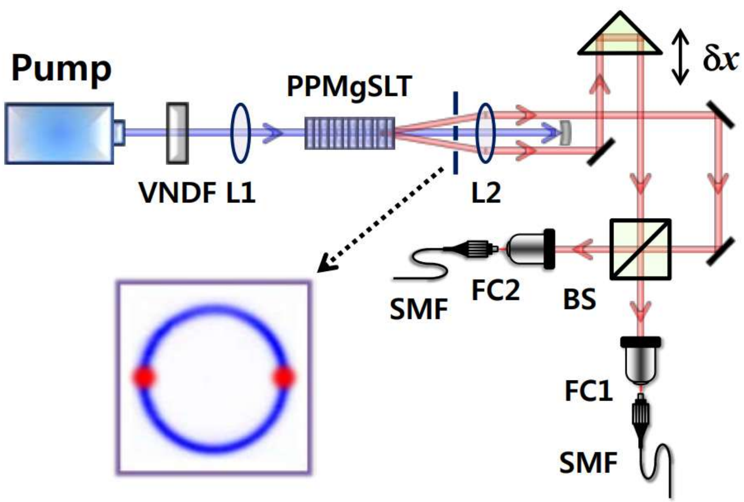
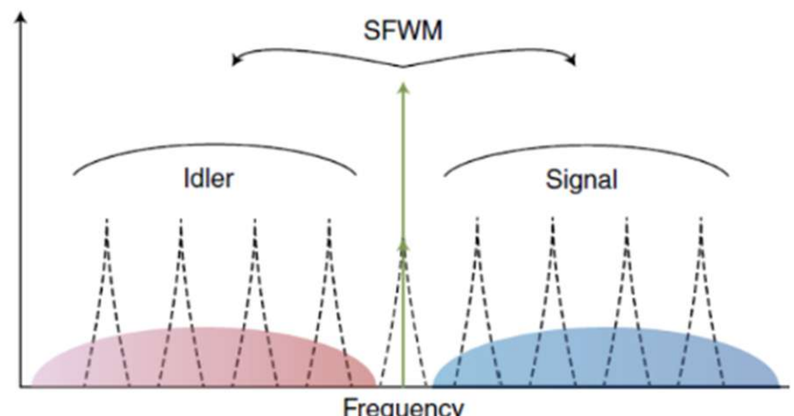
Frequency entanglement

- Photons in multiple carrier frequencies ($|\omega_0\rangle$,$|\omega_1\rangle$, $|\omega_2\rangle$,…)
- Can produce high-dimensional qudits
- Difficult to realize single qudit operation

$$|\Psi\rangle = \iint d\omega_1 d\omega_2 \Phi(\omega_1, \omega_2)\left(|\omega_1\rangle_{P1}|\omega_2\rangle_{P2} + |\omega_2\rangle_{P1}|\omega_1\rangle_{P2}\right)$$



Optics Letters, Vol. 40, Iss. 13, p. 3061-3064 (2015)



Nat Phot **13**, pages170–179 (2019)

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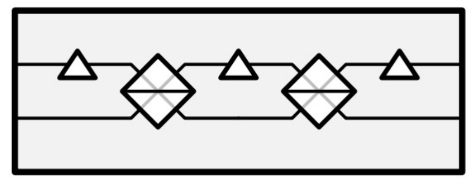
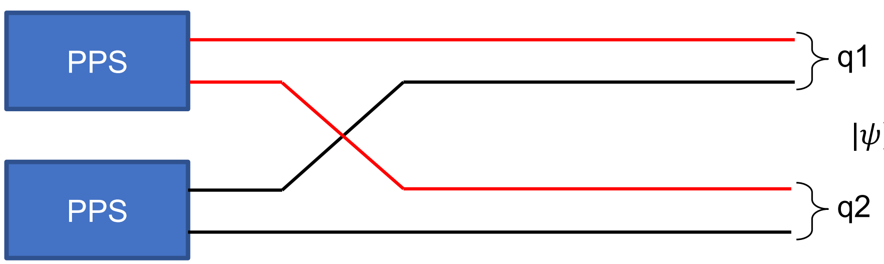
Dual-rail entanglement

- Qubit represented as photon in 1 of 2 paths ($|\text{upper}\rangle$,$|\text{lower}\rangle$)
- Can readily perform construct single qubit operations on photonics/fiber/free space platform using MZI
- Entanglement can be generated using photon pairs and postselection

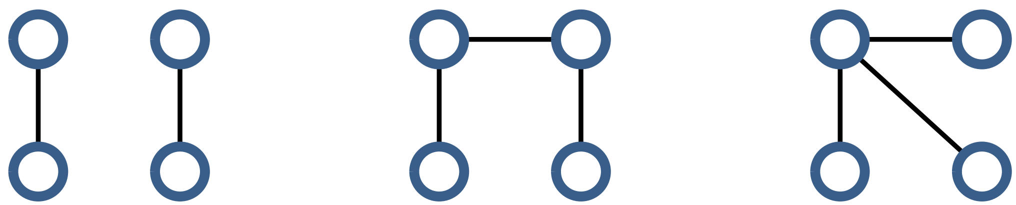




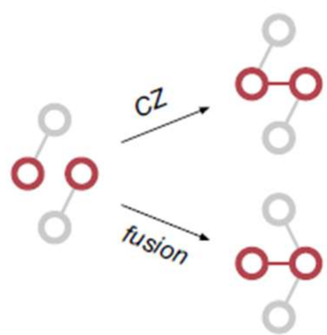
$$|\psi\rangle = |\Phi^{+}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2)$$

Cluster state

- Most basic form of entanglement: bipartite entanglement (bell states)
- Entanglement between n > 2 subsystems: cluster states, a.k.a graph states
- Greenberger-Horne-Zeilinger (GHZ) state: $|GHZ\rangle = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes n} + |1\rangle^{\otimes n})$



$|G\rangle = \prod_{(i,j)\in E} CZ_{ij}|+\rangle^{\otimes|V|}$, $s^{(i)} = \sigma_x^{(i)} \prod_{j\in N(i)} \sigma_z^{(j)}$, $s^{(i)}|G\rangle = (-1)^{\kappa_i}|G\rangle$, $\kappa_i \in \{0,1\}$



adds edge

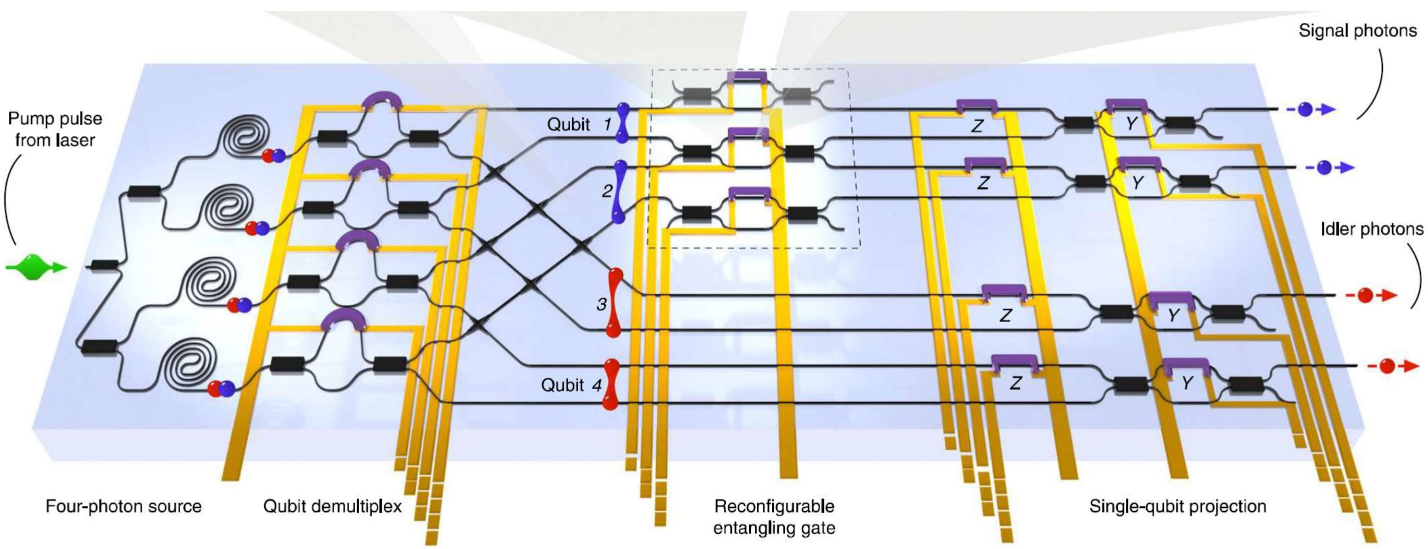
Vertex merge, vertex addition

Jeremy C Adcock *et al* 2019 *Quantum Sci. Technol.* **4** 015010

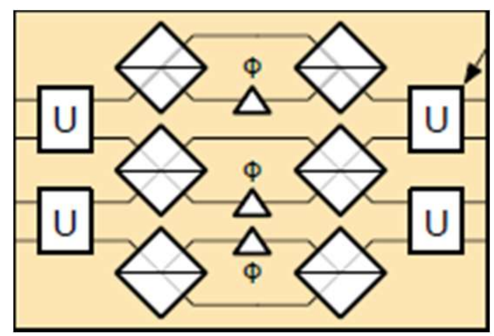
Cluster State Generation Example

- Can probabilistically entangle qubits using linear optics: R-PEG
- Generation rate falls exponentially with number of photons

Jeremy C Adcock *et al* 2019 *Quantum Sci. Technol.* **4** 015010



Nat Comm **10**, Article number: 3528 (2019)



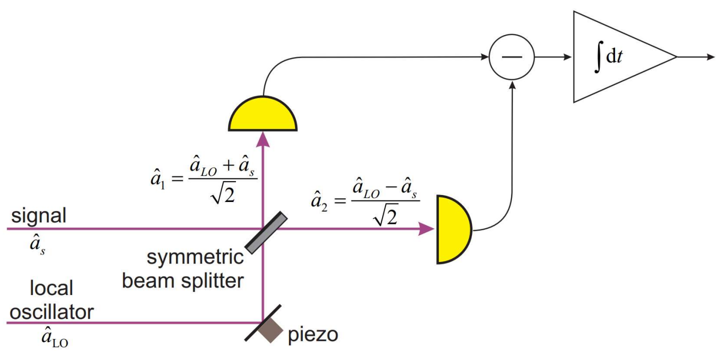
R-PEG

Squeezed light

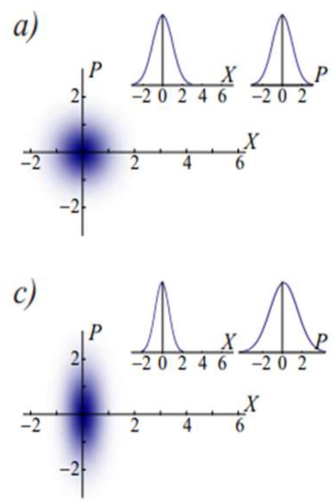
- Measuring electric field using homodyne receiver: will always be some amount of noise due to quantum nature of light

$$\langle \Delta X^2 \rangle \langle \Delta P^2 \rangle \geq 1/16$$

- Squeezing: decrease variance in one quadrature while increasing the other



arXiv:1401.4118



$$|\xi\rangle = \frac{1}{\sqrt{\cosh r}} \sum_0^\infty \frac{[(2n)!]^2}{2^n n!} \left[e^{i\phi} \tanh r\right]^n |2n\rangle$$

$$\langle \Delta X^2 \rangle = \frac{e^{-2r}}{4}$$

$$\langle \Delta P^2 \rangle = \frac{e^{2r}}{4}$$

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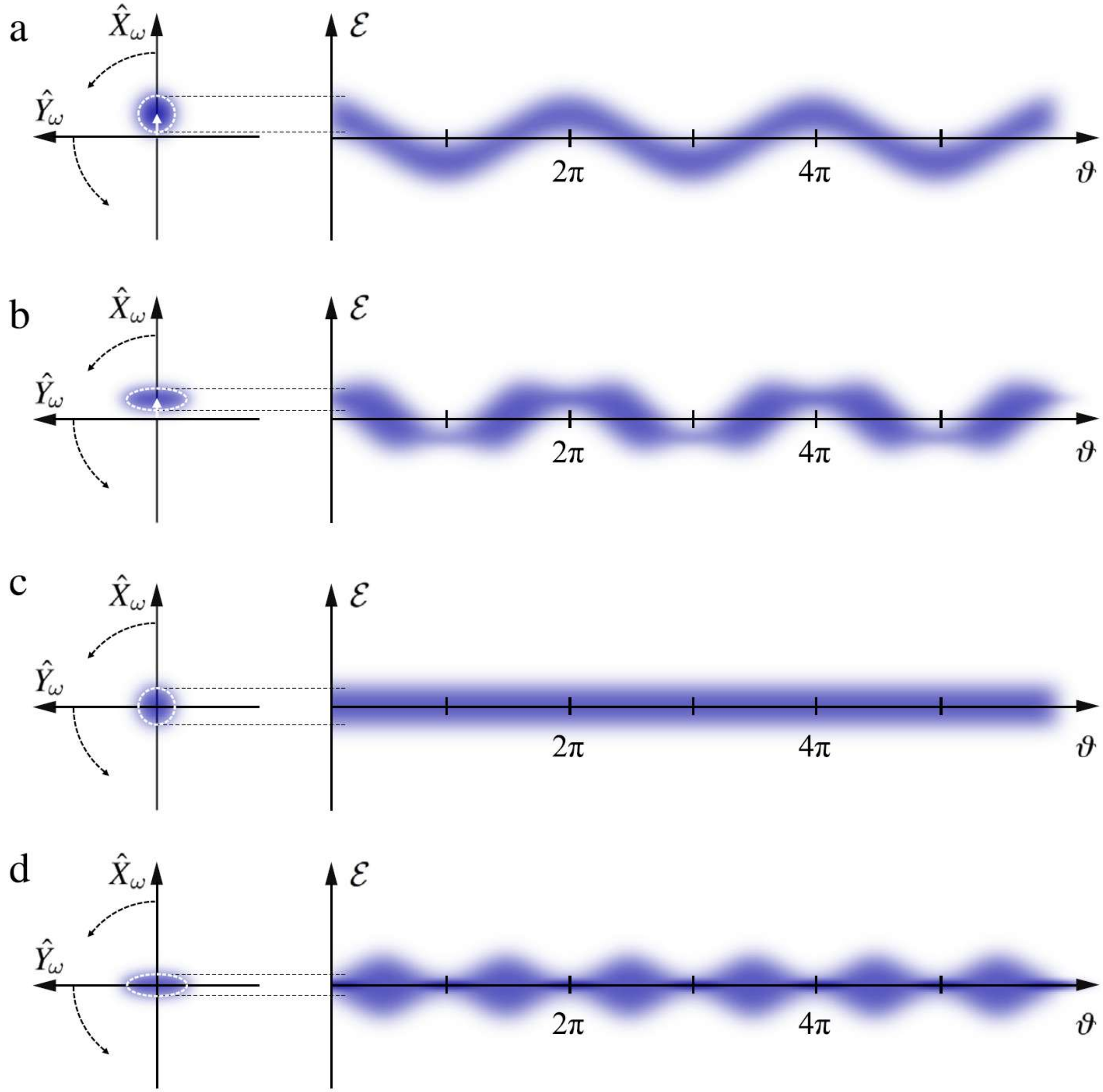


Phys Rep, Vol. 684, p. 1-51, (2017)

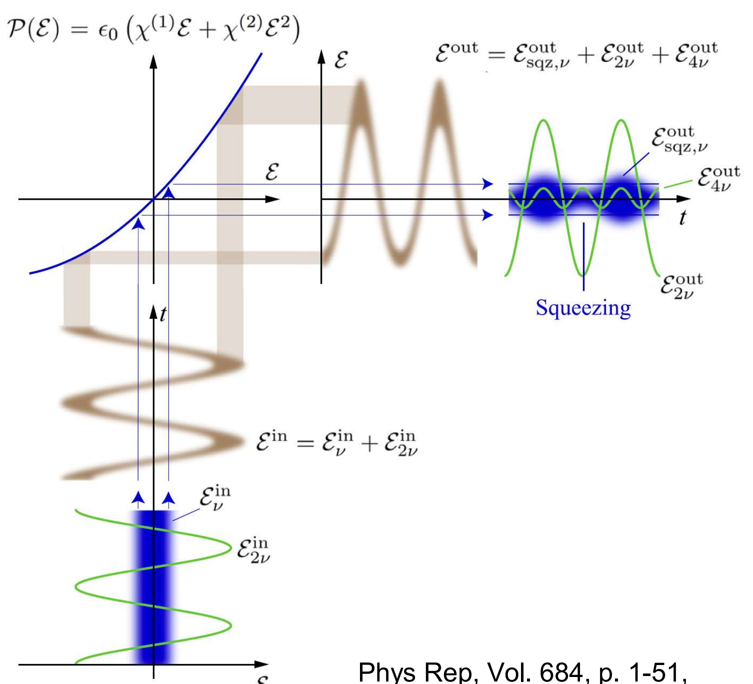
Squeezed light generation

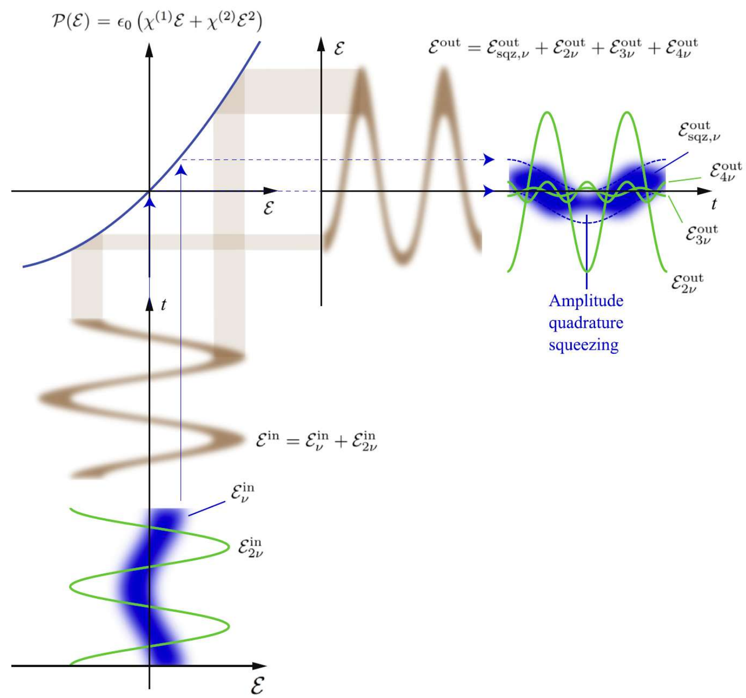
- Hamiltonian needed for squeezed light generation is same as SPDC Hamiltonian

$$H_I = i\hbar\alpha\left[e^{i\phi}\left(\hat{a}^\dagger\right)^2 - e^{-i\phi}\hat{a}^2\right] \qquad \hat{S}(\xi) = \exp\left(\xi\left(\hat{a}^\dagger\right)^2 - \xi^*\hat{a}^2\right)$$

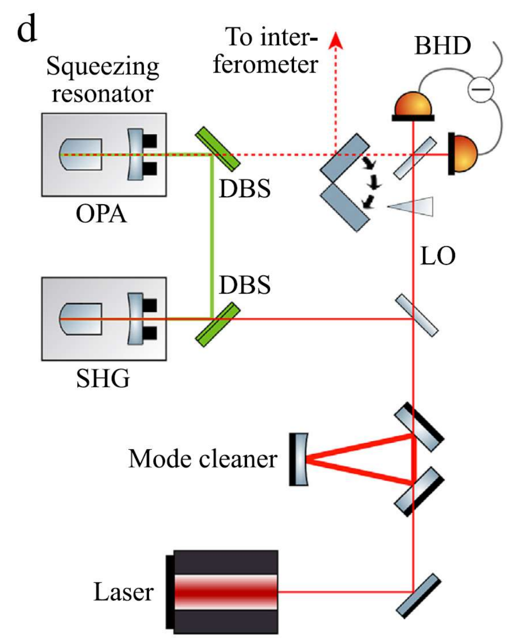
Bogoliubov transformation:

$$\hat{a}(t) = \hat{a}(0)\cosh r - \hat{a}^\dagger(0)\sinh r;$$
$$\hat{a}^\dagger(t) = \hat{a}^\dagger(0)\cosh r - \hat{a}(0)\sinh r,$$





Phys Rep, Vol. 684, p. 1-51, (2017)



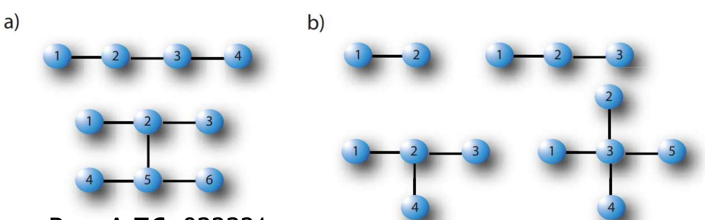
Entanglement with squeezed states: TMSV

- Simplest case of bipartite entanglement: two mode squeezed vacuum
- nondegenerate SPDC/SFWM

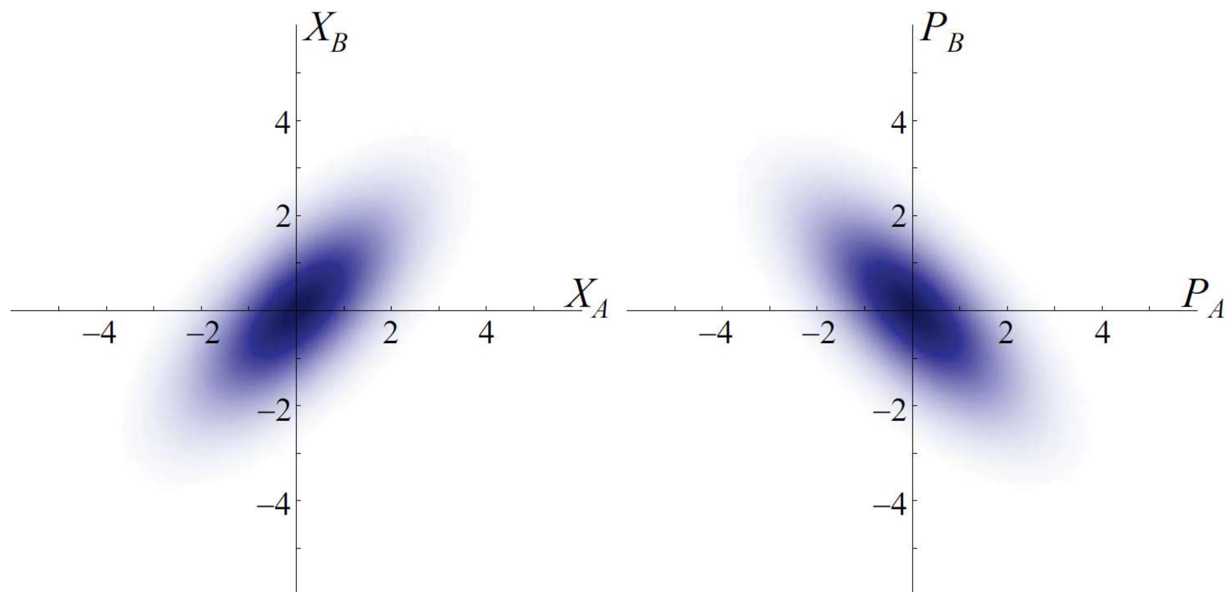
$$|\xi\rangle_{12} = \frac{1}{\cosh r}\sum_0^\infty \left[e^{i\phi}\tanh r\right]^n |n\rangle_1 |n\rangle_2$$

$$V(P_A - P_B) = e^{-2r}$$

- More complex cluster states can be created using linear optics + squeezed vacuums



Phys. Rev. A **76**, 032321



arXiv:1401.4118

15 min Break

Questions to consider during break

Overview Questions

1. What is the difference between quantum superposition and quantum entanglement?
2. How are quantum correlations different from classical correlations?
3. Why are photons the best option to distribute entanglement across distance?
4. Radio communication is more mature than optical communication. Are quantum networks at RF frequencies a good idea? Why or why not?

Quantum Sources Questions

1. How is a quantum source different from a classical source?
2. Besides size, weight, and power benefits, why use nanophotonics for quantum sources?
3. Why do many sources require a nonlinearity?

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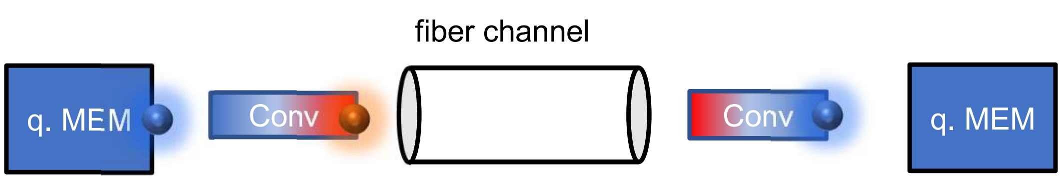
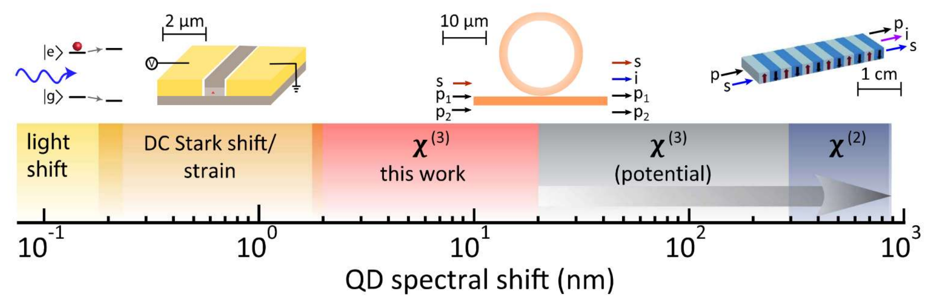
Quantum Frequency Conversion

- Platforms used to store quantum information are different than those used to communicate
- Telecom bands: 1.5 – 1.6 micron
- Diamond vacancy center: 600 – 800 nm
- Quantum dot: visible
- SQUID: MHz - GHz





Optica, Vol. 6, Iss. 5, p. 563-569 (2019)

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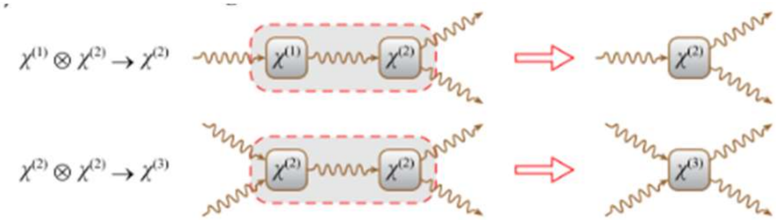
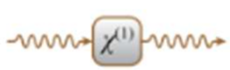
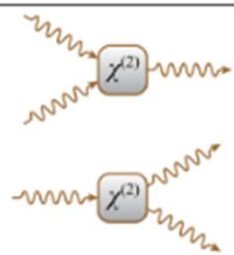
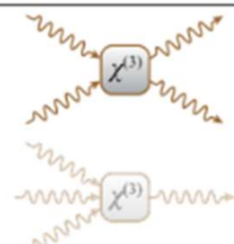
nonlinear interaction

- Need some sort of nonlinear interaction to facilitate frequency conversion
  - Optomechanics, electro-optics, optomagnonics, atomic
- Strong pump typically need to facilitate interaction, scales as $\sqrt{n_{pump}}$
- can combine nonlinearities to form an effective nonlinearity



	$\chi^{(1)}$ process	$\chi^{(2)}$ process	$\chi^{(3)}$ process
Hamiltonian	$(m_1 + m_1^\dagger)(m_2 + m_2^\dagger)$	$m_1^\dagger m_1 (m_2 + m_2^\dagger)$	$m_1^\dagger m_2^\dagger m_3 m_4 + m_1 m_2 m_3^\dagger m_4^\dagger$
Processes			
Examples	Piezoelectric Effect	Electro-optic Effect Electromechanical Effect Optomechanical Effect	Four-wave Mixing

Optica, Vol. 8, Iss. 8, p. 1050-1064 (2021)

	$\chi^{(1)}$ process	$\chi^{(2)}$ process
Electro-optic (EO)	Energy Mismatch	Electro-optic Modulator $H_{eo} = \hbar g_{eo,0} a^\dagger a (b + b^\dagger)$
Electromechanical (EM)	Piezoelectric Effect $H_{pz} = \hbar g_{pz} (b + b^\dagger)(m + m^\dagger)$	Moving Capacitor $H_{em} = \hbar g_{em,0} b^\dagger b (m + m^\dagger)$
Optomechanical (OM)	Energy Mismatch	Radiation Pressure $H_{om} = \hbar g_{om,0} a^\dagger a (m + m^\dagger)$
Magneto-optical (MO)	Energy Mismatch	Faraday Effect $H_{mago} = \hbar g_{mago,0} a^\dagger a (m + m^\dagger)$

resonator-based conversion

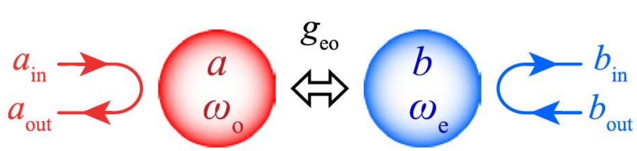
- Can use Heisenberg equation and input-output relation of resonator to determine efficiency of interaction

$$\dot{\mathbf{a}}(t) = \mathbf{A}\mathbf{a}(t) + \mathbf{B}\mathbf{a}_{\mathbf{in}}(t), \qquad \mathbf{a}_{\mathbf{out}}(t) = \mathbf{B}^T\mathbf{a}(t) - \mathbf{a}_{\mathbf{in}}(t),$$

- Conversion efficiencies are given in terms of cooperativities and extraction ratios

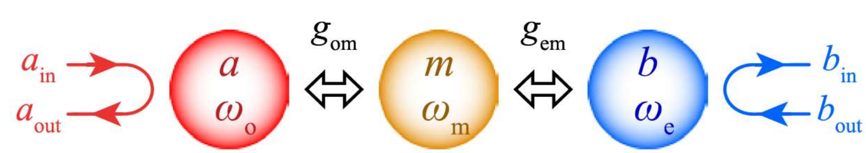
$$C_{ij} = \frac{4g_{ij}^2}{\kappa_i\kappa_j}, \eta_i = \frac{\kappa_{i,ext}}{\kappa_i}$$

direct:



$$\eta = \eta_o\eta_e\frac{4C_{eo}}{(1+C_{eo})^2},$$

single intermediate stage:



$$\eta = \eta_o\eta_e\frac{4C_{om}C_{em}}{(1+C_{om}+C_{em})^2}.$$

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Noise and bandwidth

- Sources of noise are thermal and spurious nonlinear interaction
- For microwave-to-optical, thermal is dominant source of noise

$$n_{\mathrm{add(down)}} = \frac{1-\eta_{\mathrm{e}}}{\eta_{\mathrm{o}}} \frac{1}{C_{\mathrm{eo}}} \bar{n}_{\mathrm{th,e}}$$

$$n_{\mathrm{add(up)}} = \left(\frac{1}{\eta_{\mathrm{e}}} - 1\right) \bar{n}_{\mathrm{th,e}}$$

$$n_{\mathrm{add,e(down)}} = \frac{1-\eta_{\mathrm{e}}}{\eta_{\mathrm{o}}} \frac{(1+C_{\mathrm{om}})^2}{C_{\mathrm{om}} C_{\mathrm{em}}} \bar{n}_{\mathrm{th,e}}, \quad n_{\mathrm{add,e(up)}} = \left(\frac{1}{\eta_{\mathrm{e}}} - 1\right) \bar{n}_{\mathrm{th,e}},$$

$$n_{\mathrm{add,m(down)}} = \frac{1}{\eta_{\mathrm{o}} C_{\mathrm{om}}} \bar{n}_{\mathrm{th,m}} \qquad n_{\mathrm{add,m(up)}} = \frac{1}{\eta_{\mathrm{e}} C_{\mathrm{em}}} \bar{n}_{\mathrm{th,m}}$$

- Bandwidth of interaction limited by coupling efficiency

$$B \sim (\kappa_{\mathrm{o}}^{-1} + \kappa_{\mathrm{e}}^{-1})^{-1}$$

$$B \sim \left(\kappa_{\mathrm{o}}^{-1} + \kappa_{\mathrm{e}}^{-1} + \frac{g_{\mathrm{em}} g_{\mathrm{om}}}{\sqrt{\kappa_{\mathrm{o}} \kappa_{\mathrm{e}}}}\right)^{-1}$$

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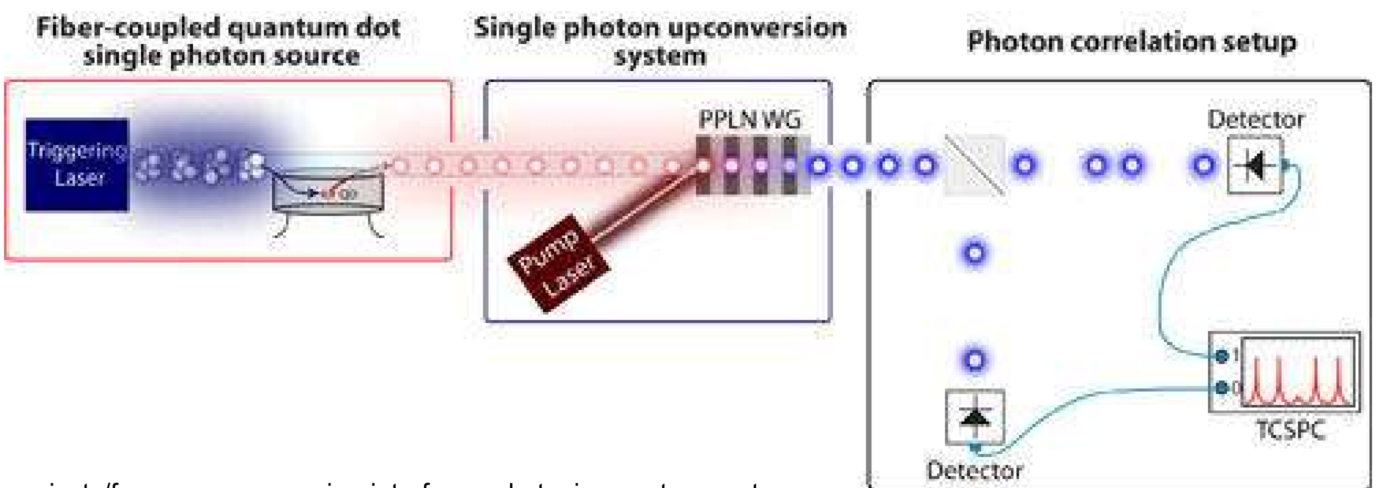
Optical QFC

- Optical nonlinearity used for single photon/squeezed light generation can also be used for QFC
- Have to worry about spurious nonlinear processes with pump (fluorescence, Raman scattering)
- Up to 24% efficiency realized using PPLN

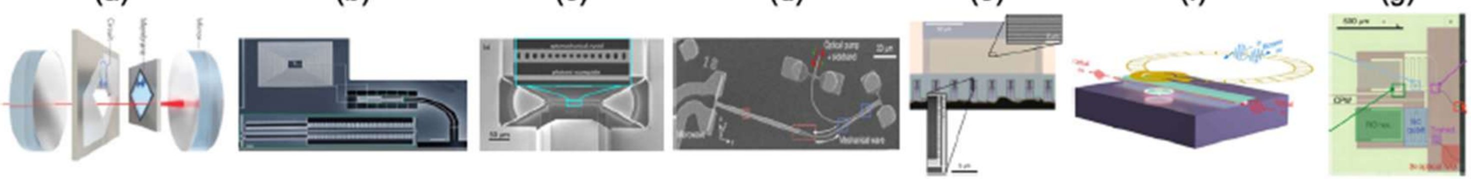


https://www.nist.gov/programs-projects/frequency-conversion-interfaces-photonic-quantum-systems

optomechanical frequency conversion

- phonons: vibrational modes at microwave frequencies & optical wavelengths
- can obtain high cooperativities
- Bulk: high Q, integrated: large mode overlap and small mode volume
- Acoustic transduction efficiency very low

	MHz Electro-Optomechanics		GHz Piezo-Optomechanics				
	(a)	(b)	(c)	(d)	(e)	(f)	(g)



	(a)	(b)	(c)	(d)	(e)	(f)	(g)
$g_{\mathrm{om},0}$ [Hz]	6.6	0.66×10^6	115×10^3	80×10^3	1.3×10^6	19×10^3	$\sim 0.5 \times 10^6$
C_{om}	132	0.9	3×10^{-3}	5×10^{-3}	1.7	0.4	0.04
C_{em}	132	0.57	–	–	–	7	~ 150
η	0.47	1.9×10^{-4}	10^{-8}	10^{-5}	$< 3.5 \times 10^{-10}$	7.4×10^{-4}	8.8×10^{-6}
η_{in}	0.99	0.016	NR	0.026	NR	0.058	10^{-3}
$\frac{B}{2\pi}$ [MHz]	0.012	3.7×10^{-4}	~ 1	~ 1	NR	1	1
n_{add}	38	$\sim 10^4$	NR	NR	NR (*)	NR	0.57 (**)
T_{env} [K]	0.035	0.15	~ 300	~ 300	0.02	0.9	0.015

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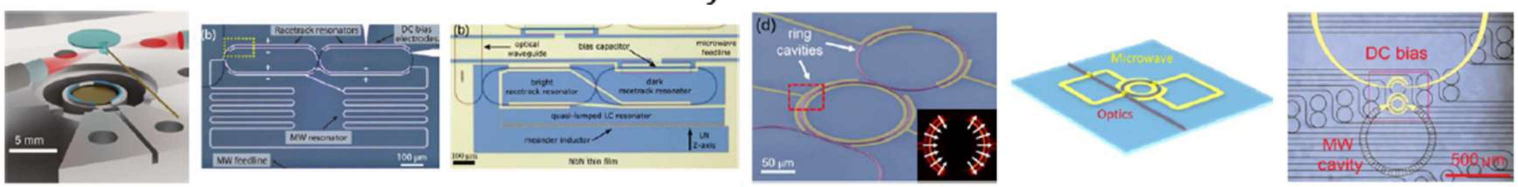
electro-optic frequency conversion

- direct conversion: electric field used to modulate optical refractive index

$$\Delta\left(\frac{1}{n^2}\right) = \sum_{j=1}^{3} r_{ij} E_j$$



$\frac{g_{eo,0}}{2\pi}$ [Hz]	36	1200	650	750	310	42
C_{eo}	1.7×10^{-3}	NR	NR	0.041	0.075	3×10^{-4}
η	3.16×10^{-4} (2.3×10^{-7})	6.6×10^{-6}	2.7×10^{-5}	0.01	0.02	2.4×10^{-5} $(\sim 3.3 \times 10^{-6})$
η_{in}	6.7×10^{-3} $(\sim 5 \times 10^{-6})$	NR	NR	0.152	0.259	0.0012 (NR)
$\frac{B}{2\pi}$ [MHz]	9	20	13	NR	0.59	2.9
n_{add}	$5.5/\eta$ $(0.03/\eta)$	NR	NR	NR	NR	NR (∗) (NR (∗))
T_{env} [K]	0.32 (0.007)	1	1	1.9	2	∼0.15 (0.04)

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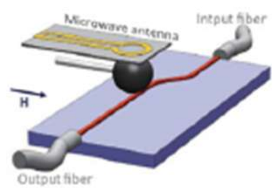
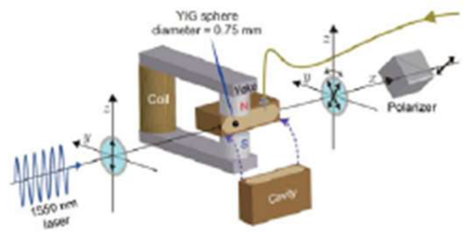
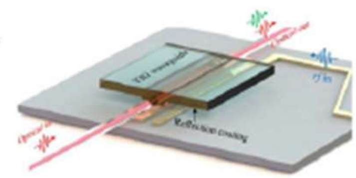
magnon-mediated conversion

- Magnetic devices: large tunability and broad bandwidth, yttrium iron garnet (YIG)
- Strong coupling seen between magnons and microwave photons via linear magnetic dipole interaction
- Magnon-optical photons interaction: faraday effect, $\Delta\theta = \mathcal{v}Bd$







$\frac{g_{\mathrm{mago},0}}{2\pi}$	[Hz]	0.33	3.3×10^{-4}	17.2
$\frac{C_{\mathrm{mago}}}{2\pi}$	[Hz]	5.4×10^{-10}	–	4.06×10^{-7}
$\frac{C_{\mathrm{mage}}}{2\pi}$	[Hz]	–	510	0.8
η		1.7×10^{-15}	10^{-10}	1.08×10^{-8}
η_{in}		6×10^{-6}	NR	5.19×10^{-7}
$\frac{B}{2\pi}$	[MHz]	NR	NR	16.1
T_{env}	[K]	~ 300	~ 300	~ 300

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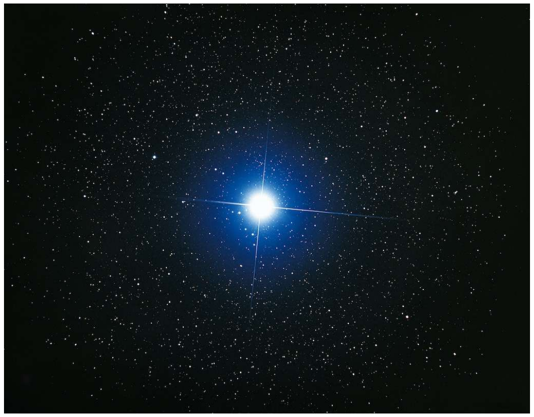
Transmission



Sirius: the brightest star in the sky
image from space.com

Free Space

Lenses and mirrors

Waveguides

Optical Fiber

Important: No amplifiers allowed in the channel

No-cloning theorem prevents “copying” of quantum state. Amplification is like copying.

Loss / Distance Tradeoffs

Economics/logistics require lower number of repeaters

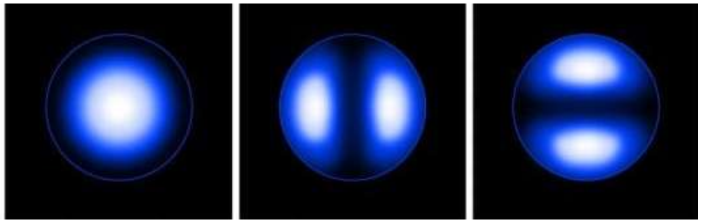
Loss requires high number of repeaters

Free Space

- Reflections
- Detector surfaces
- Misaligned optical elements
- Atmospheric turbulence
- Particle Scattering
- Dispersion

Fiber

- Single mode vs multimode
- Wavelength-dependent loss
- Lowest loss ~0.2 dB/km at 1550 nm --- about 25 km $1/e$ attenuation length
- Most attractive quantum sources emit light a wavelengths **shorter** than 1550 nm
- Coupling loss to/from fiber a significant challenge

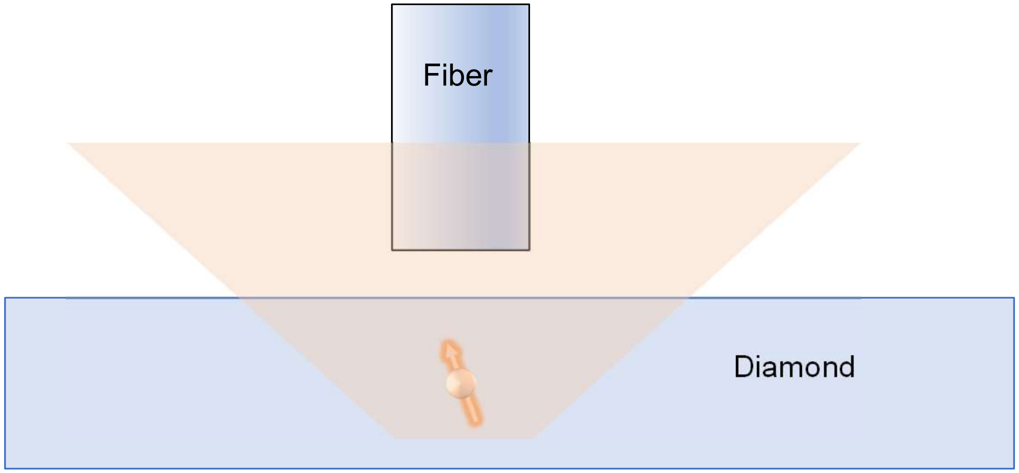


Fiber coupling loss case study

- Efficient spin-photon interfaces required for high entanglement generation rates
- Entanglement generation rate decays linearly with channel efficiency η
- Maximum rate for single link is $-\log_2(1-\eta) \approx 1.44\eta$

Major bottleneck just getting the photons out of the emitters!

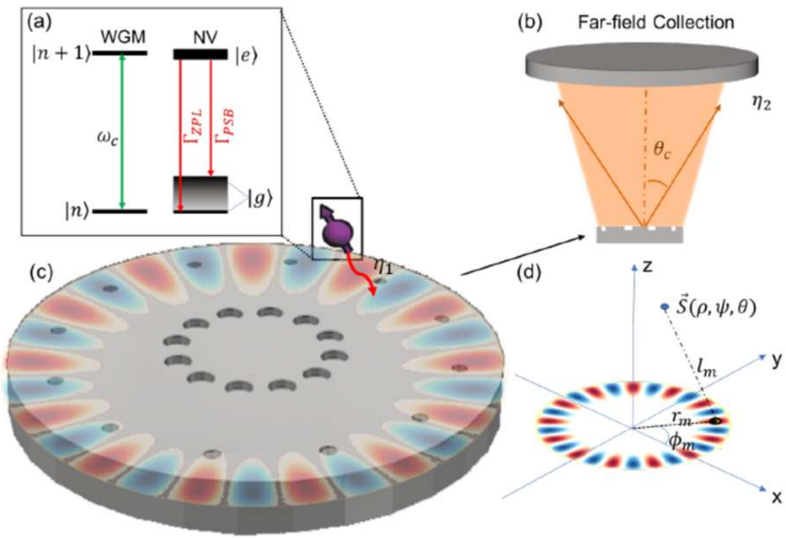
1. Poor emission into zero phonon line
2. Poor photon collection efficiency



Question: How can we increase η?

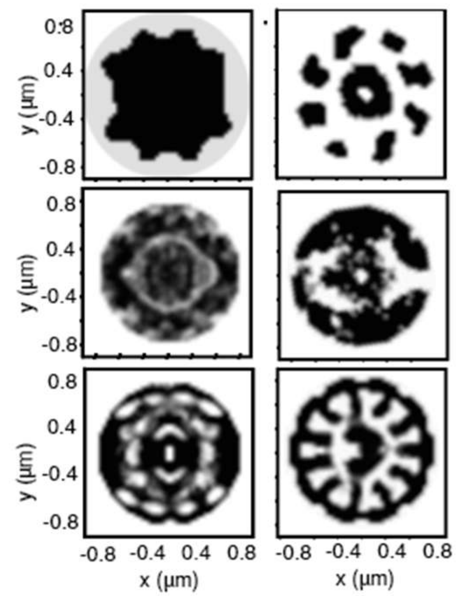
Example: Coupling to photonic emitters

- Break efficiency into two parts: $\eta = \eta_1 \eta_2$
- Design nanophotonic structure to optimize η



Duan et al, arXiv:2105.05695 (2021).

- Increase η using topology optimization



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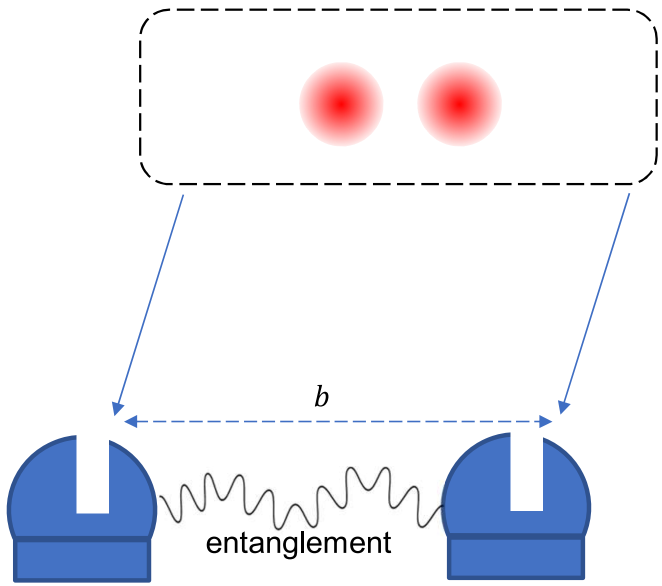
Quantum Telescope

Questions:
What sources of losses need to be considered?
What tradeoffs are there between fiber/free space for this application?



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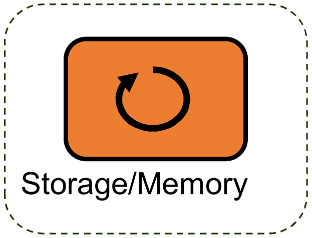
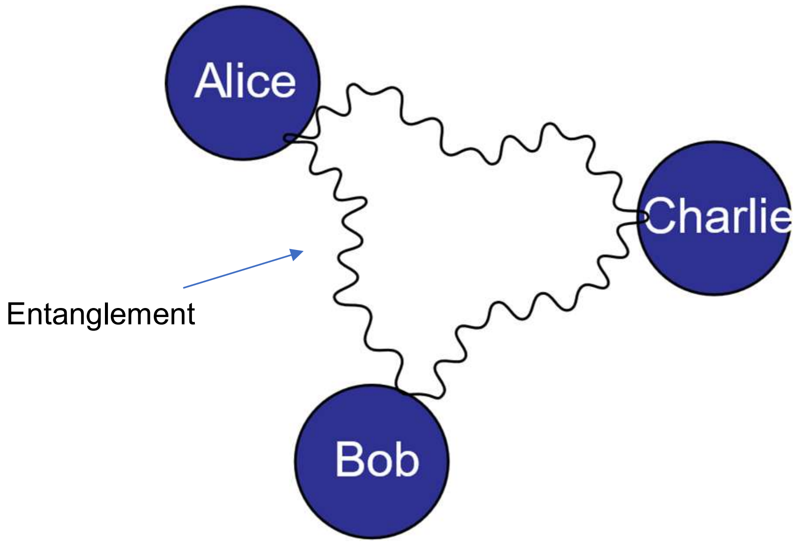
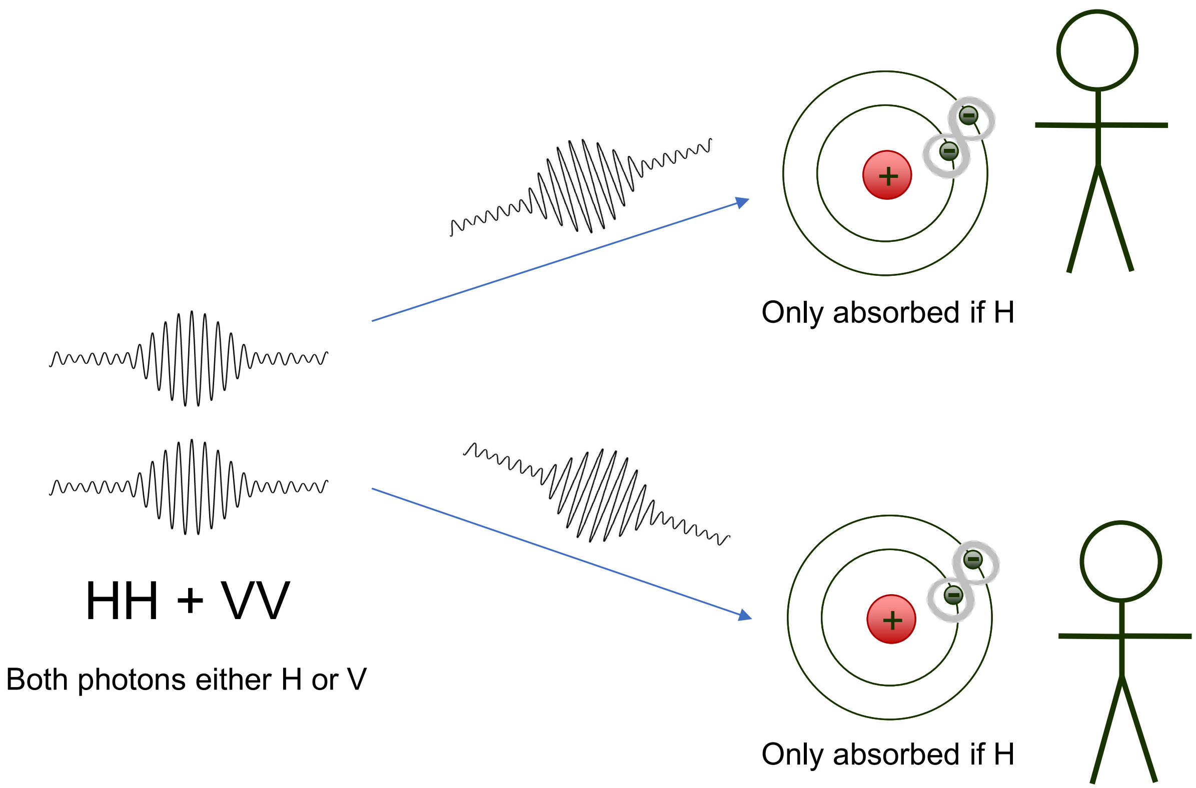


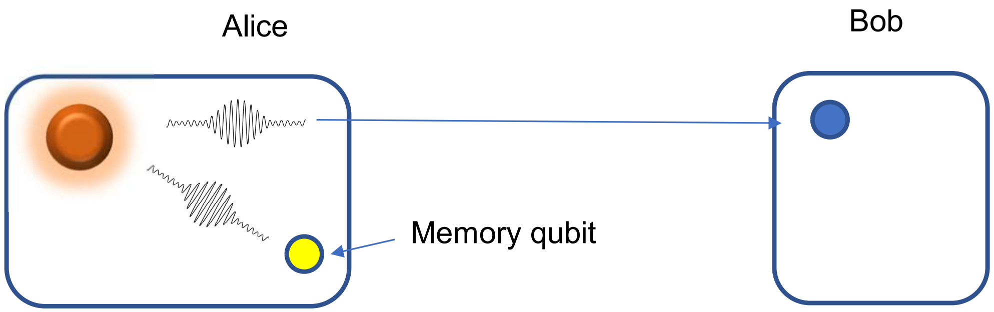
Quantum Memories / Repeaters



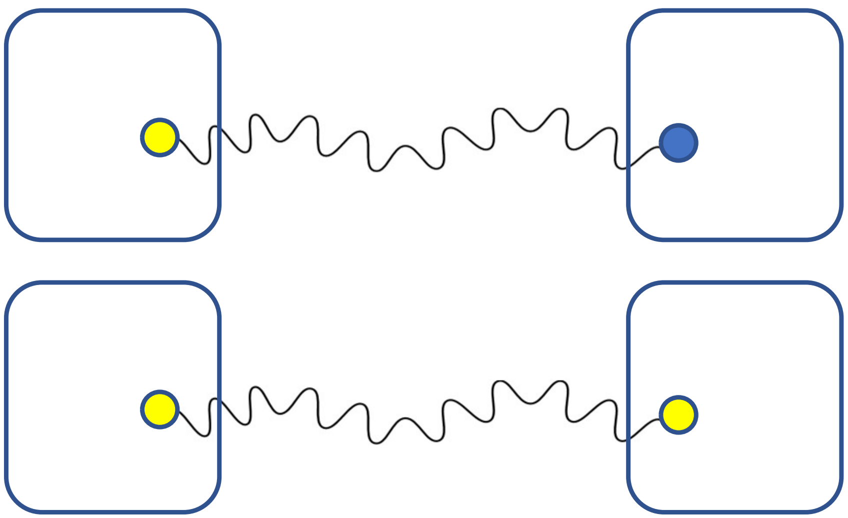
Review: Distribute Entanglement



Quantum memory for link-level entanglement



Alice needs memory qubit to preserve entanglement during transmission of second photon



Bob can make direct measurement of photon using detector

Or…

Bob can transfer quantum state to memory qubit for later analysis

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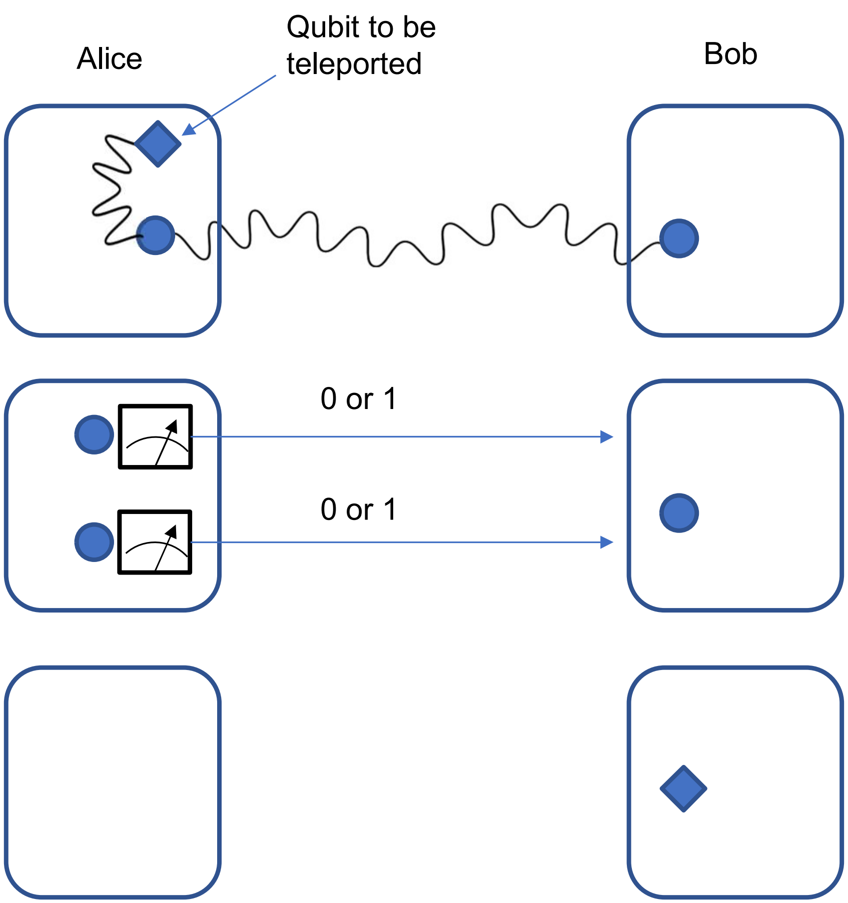
Example Operation: Quantum Teleportation



1. Prepare Entanglement

2. Alice Measures, destroying entanglement. Sends results to Bob.

3. Bob uses result to transform his qubit into Alice's original qubit

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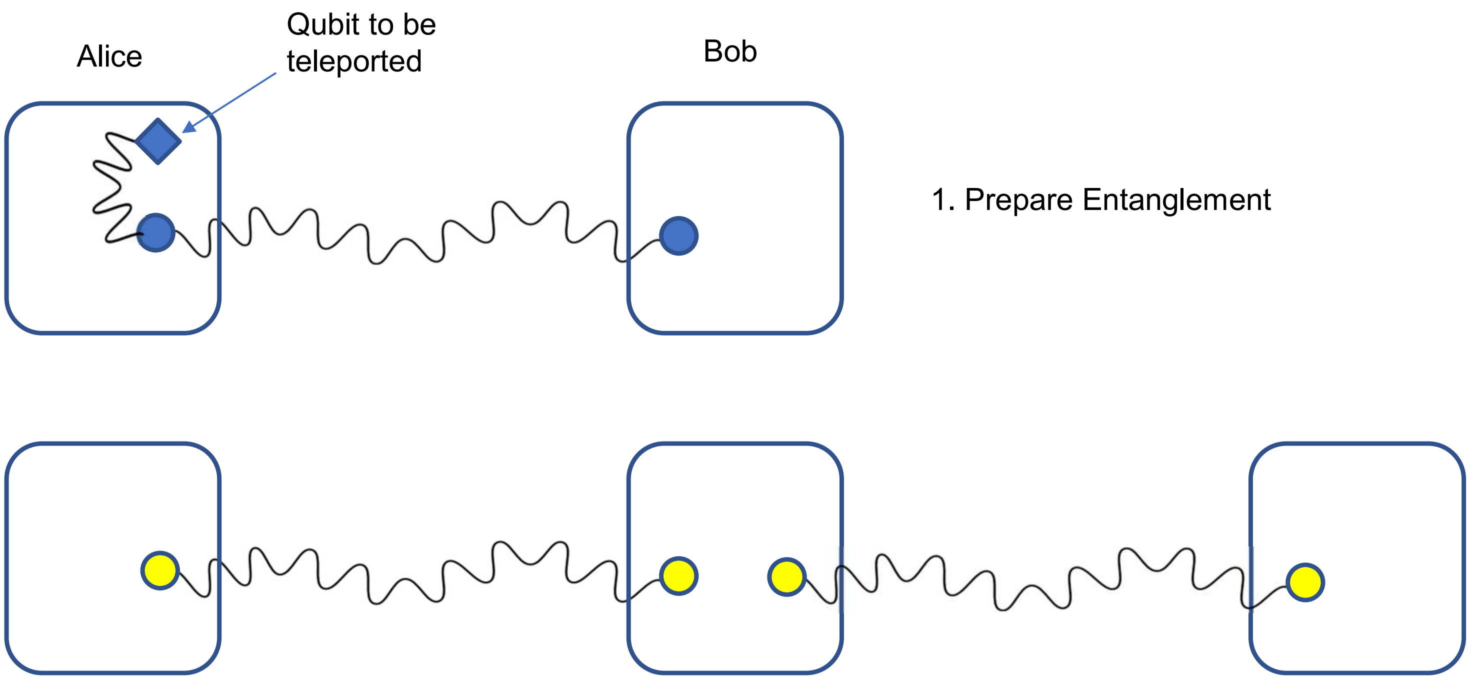
Extension of link-level entanglement



1. Prepare Entanglement

Purification
Entanglement Swapping
Logic

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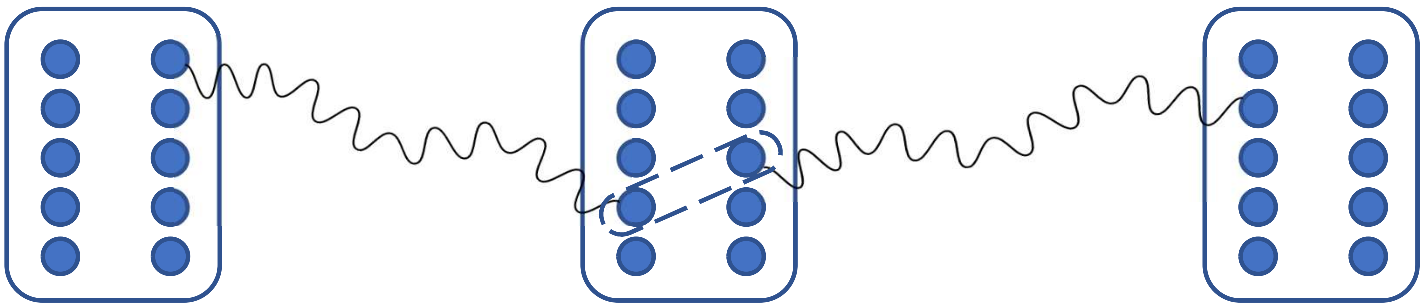
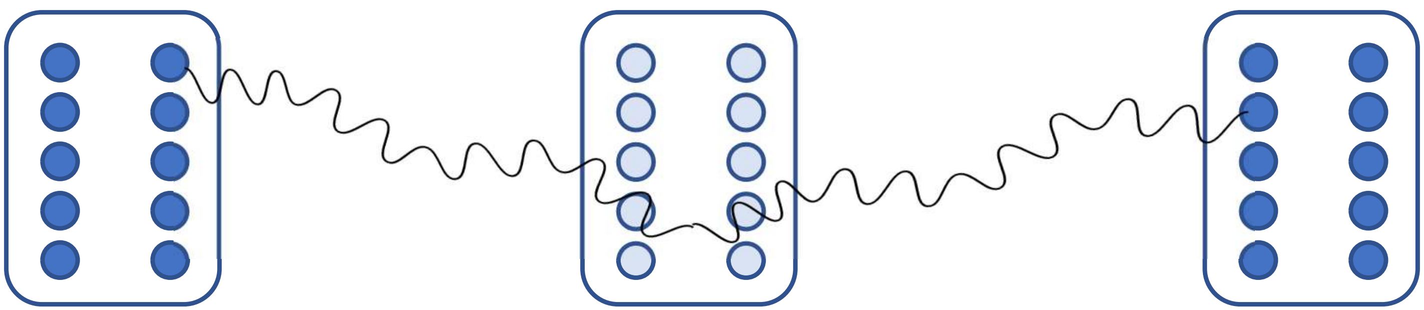
Extension of entanglement





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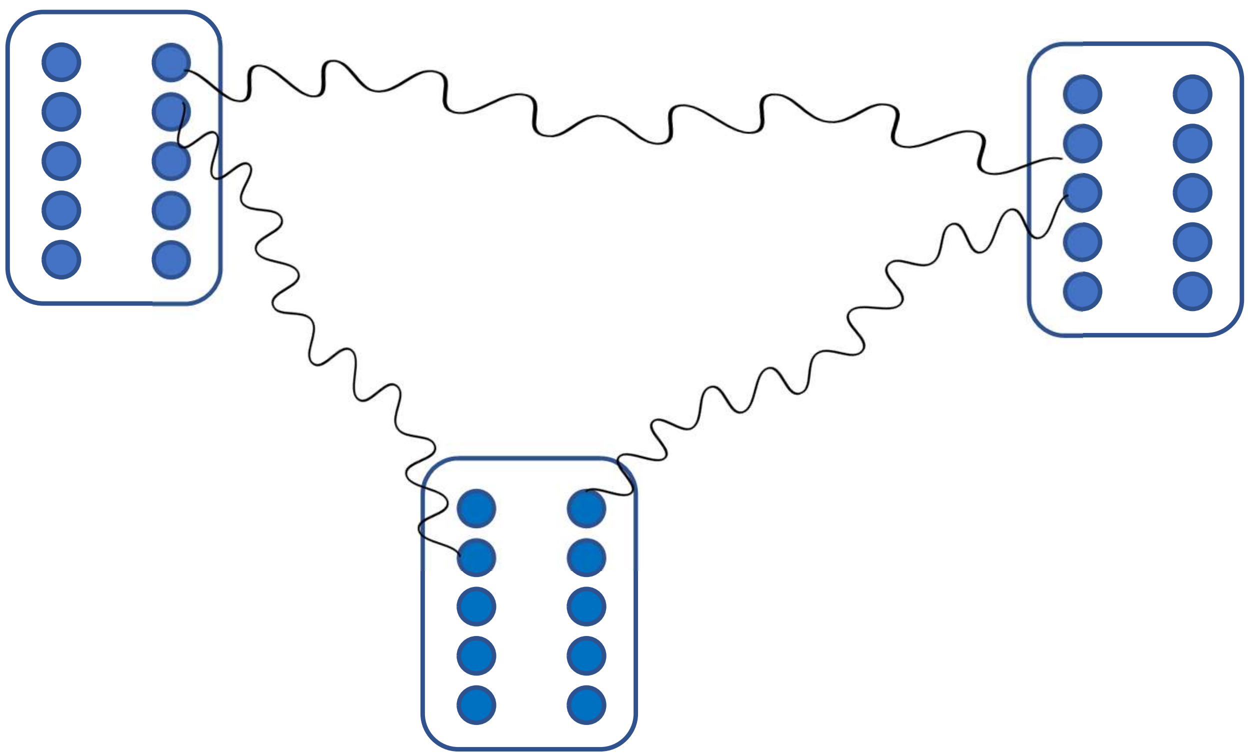
Multi-party entanglement



The need for a quantum memory

- Timing / synchronization / scheduling
- Critical for quantum repeater

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Many types of memory being explored

- Ground/Excited States of atoms
- Electron spin
- Nuclear spin
- Relative position
- Solid state (Defect centers, quantum dots) vs isolated atoms (Rydberg, Trapped Ions)
- Superconducting Josephson junctions

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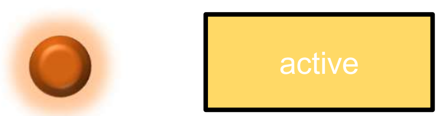
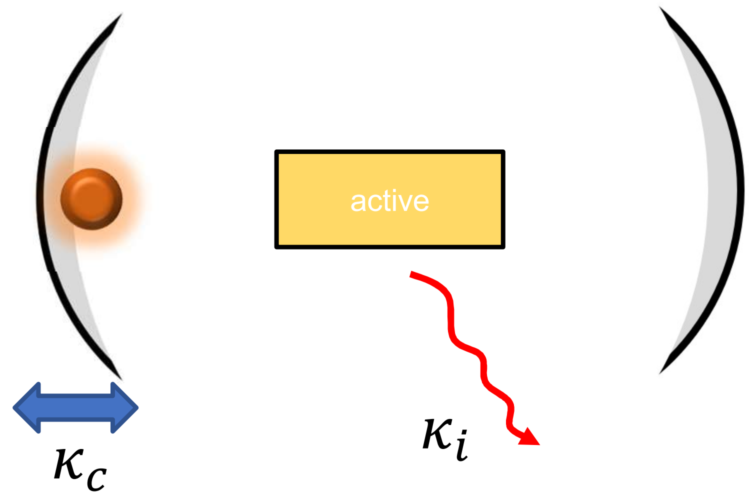
Cavity Enhancement

- Strength of many interactions can be enhanced using a resonator cavity

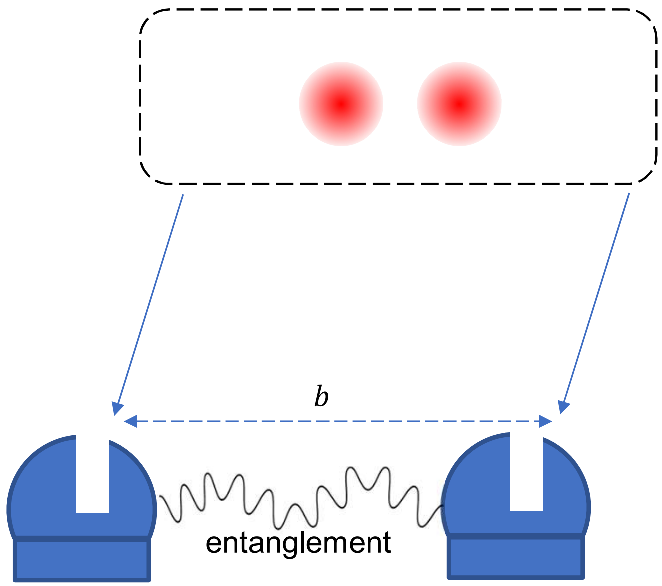


- $Q = 2\pi \dfrac{\text{energy stored}}{\text{energy dissipated per cycle}} = \dfrac{\omega}{\kappa}$
- Strength of interaction $\propto Q$ (Purcell factor)



Telescope Application

Questions:
Where would quantum memories be used in a quantum telescope?
What tradeoffs should one consider in choice of memory?

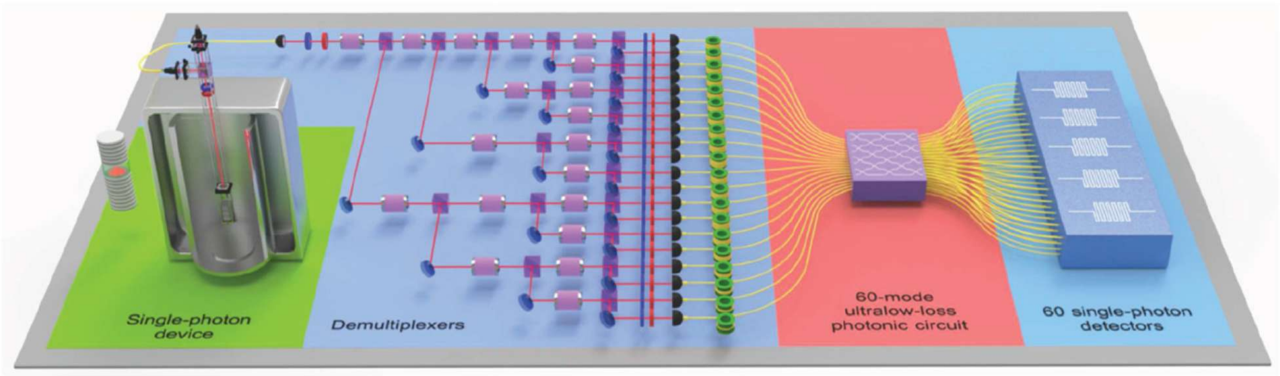


What is a quantum detector?

- For a lot of quantum applications, relevant quantum state is encoded on the single photon level
- Relevant metrics:
  - Detection efficiency
  - Dark count rate
  - Dead time
  - Timing jitter

$$R_{SK} \propto \eta \cdot f \cdot u \cdot L$$

$$R_{BE} \propto R_{dc}/R_{SK}$$



Phys. Rev. Lett. **123**, 250503

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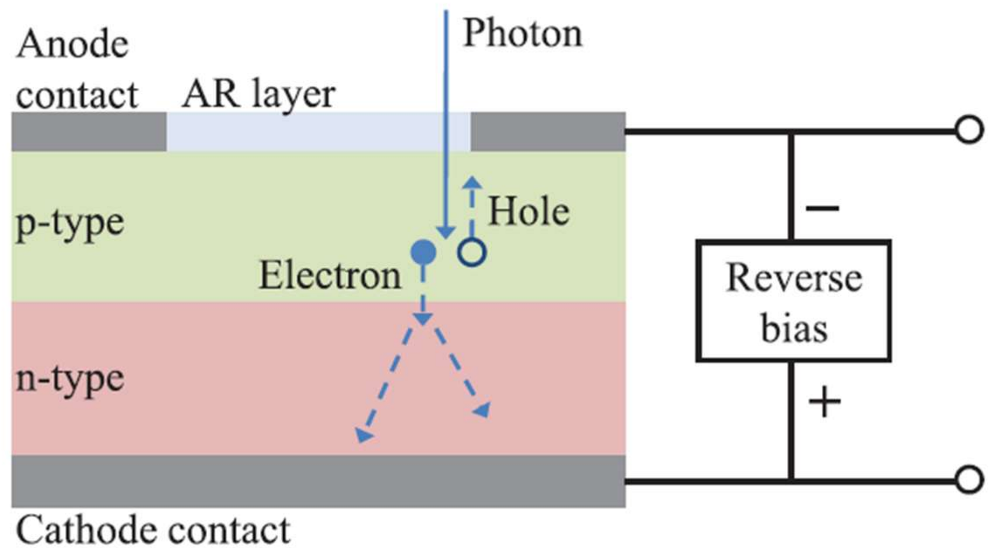
SPAD

- SPAD: single photon avalanche diode
- diode operated in “gieger mode”: reverse bias voltage greater than breakdown voltage, absorption of photon causes avalanche of current
- efficiency up to 85%
- dark count reduced by reducing temperature (210 K - 250 K)
- dead time from trap sites that need to be depopulated: 10s of ns to 10 us
- timing jitter + efficiency dependent on thickness of absorption layer
- Has been paired with up-conversion process to increase detection efficiency



Rev. Sci. Instrum., 82 (2011), p. 071101

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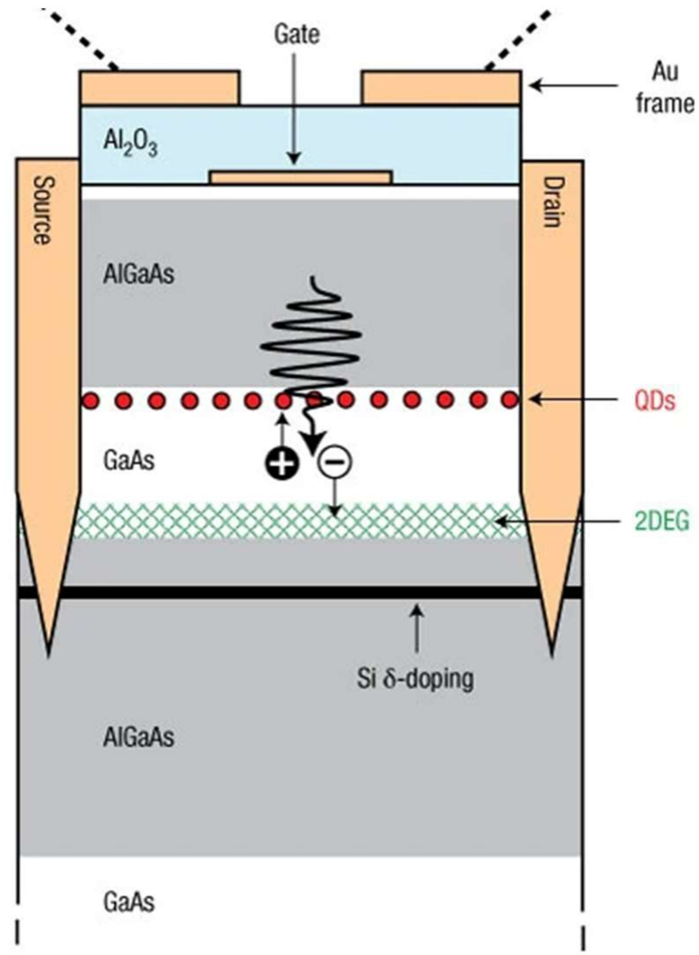
QDOGFET

- QDOGFET: quantum dot field-effect transistor-based detector
- optical absorber with thin layer of Q dots between gate and channel
- photo-generated charges trapped in Q dots, which changes channel conductance
- low detection efficiency (~2-12%), low dark count probability (0.003)

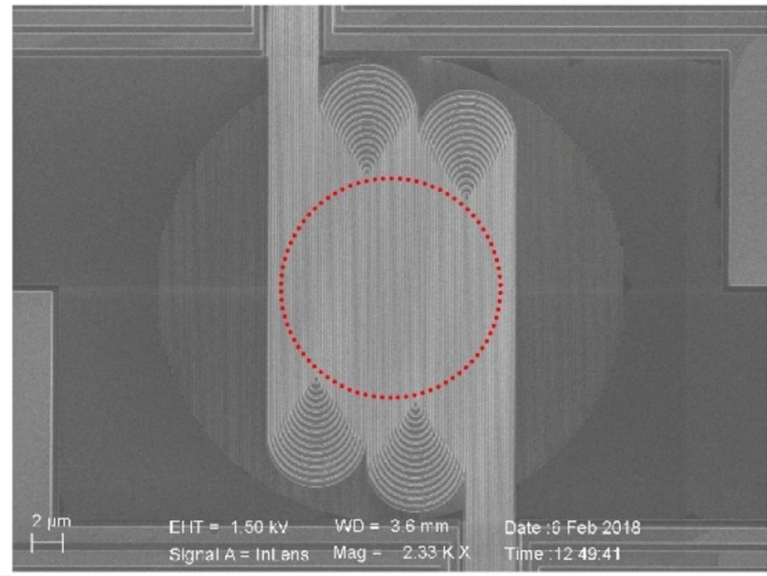


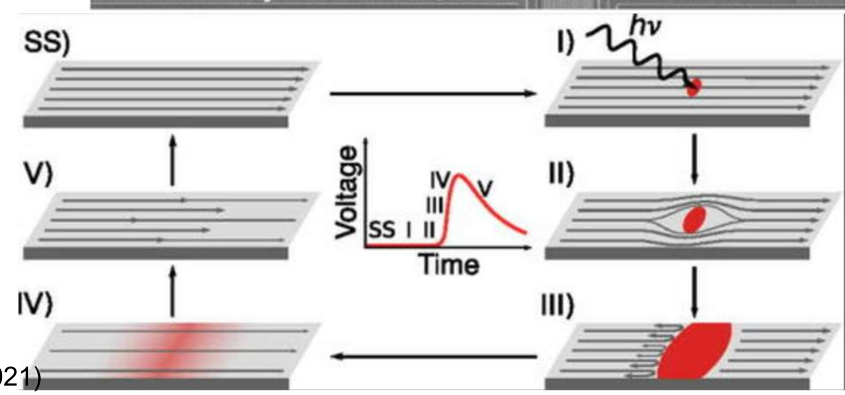
Nat Phot 1, 585-588 (2007)

Superconducting Detectors

- Superconducting detectors: transition edge sensor (TES), superconducting tunnel junction (STJ), microwave kinetic inductance detector (MKID)
- SNSPD: superconducting nanowire single photon detector
- narrow superconducting wire biased just below critical current density
- absorption of photon causes wire to transition from superconducting to normal resistance (cooper pair breaking), which results in voltage spike
- require cooling to 4 K or less
- very fast, time jitter < 50 ps
- with use of cavities, efficiency of > 90% has been achieved

arXiv:2006.00411

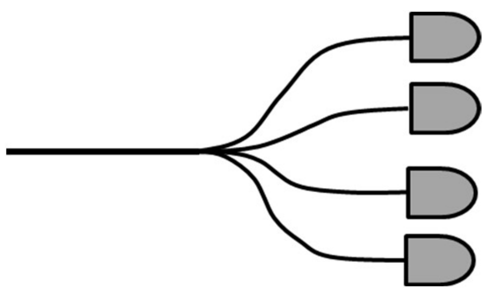




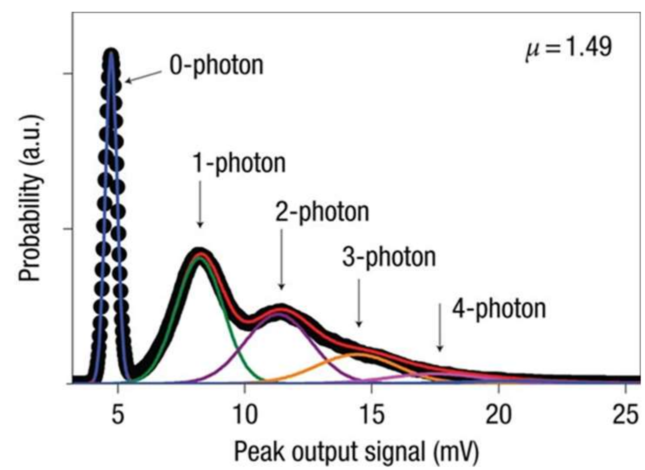
Appl. Phys. Lett. **118**, 190502 (2021)

PNR capability

- PNR: photon number resolving
- most detectors cannot by default detect multiple photons arriving simultaneously
- some single photon detectors can detect multiple photons by carefully studying the response curve
- pseudo-PNR detector: use space/time multiplexing to detect multiple photons with some probability


SPD array

Nat Phot 2, 425-428 (2008)



Detector type	Operation temperature (K)	Detection efficiency, wavelength η(%), λ (nm)	Timing jitter, δt(ns) (FWHM)	Dark-count rate, D (ungated) (1/s)	Figure of merit	Max. count rate ($10^6/s$)	PNR capability
PMT (visible–near-infrared)	300	40 @ 500	0.3	100	1.3×10^7	10	Some
PMT (infrared)	200	2 @ 1550	0.3	200 000	3.3×10^2	10	Some
Si SPAD (thick junction)	250	65 @ 650	0.4	25	6.5×10^7	10	None
Si SPAD (shallow junction)	250	49 @ 550	0.035	25	5.6×10^8	10	None
Si SPAD (self-differencing)	250	74 @ 600	...	2000	...	16	Some
Si SPAD (linear mode)	78	56 @ 450	...	0.0008	...	0.01	Full[a]
Si SPAD (cavity)	78	42 @ 780	0.035	3500	3.4×10^6	10	None
Si SPAD (multipixel)	290	40 @ 532	0.3	25 000–500 000	1×10^4	30	Some
Hybrid PMT (PMT + APD)	270	30 @ 1064	0.2	30 000	5×10^4	200	None
Time multiplexed (Si SPAD)	250	39 @ 680	0.4	200	5×10^6	0.5	Some
Time multiplexed (Si SPAD)	250	50 @ 825	0.5	150	7×10^6	2	Some
Space multiplexed (InGaAs SPAD)	250	33 @ 1060	0.133	160 000 000	1.6×10^1	10	Some
Space multiplexed (InGaAs SPAD)	250	2 @ 1550	...	...	...	0.3	None
InGaAs SPAD (gated)	200	10 @ 1550	0.370	91	3.0×10^5	0.01	None
InGaAs SPAD (self-differencing)	240	10 @ 1550	0.055	16 000	1.1×10^5	100	None
InGaAs SPAD (self-differencing)	240	10 @ 1550	...	...	...	...	Full
InGaAs SPAD (discharge pulse counting)	243	7 @ 1550	...	40 000	...	10	None
InP NFAD (monolithic negative feedback)	243	6 @ 1550	0.4	28 000	5×10^3	10	Some
InGaAs (self-quenching and self-recovery)	300	... @ 1550	10	...	–	3	Some
CIPD (InGaAs)	4.2	80 @ 1310	...	...	...	0.001	Full
Frequency up-conversion	300	8.8 @ 1550	0.4	13000	1.7×10^4	10	None
Frequency up-conversion	300	56-59@ 1550	...	460000	...	5	None
Frequency up-conversion	300	20 @ 1306	0.62	2200	1.5×10^5	10	None
VLPC	7	88 @ 694	40	20000	1.1×10^3	10	Some
VLPC	7	40 @ 633	0.24	25000	6.7×10^4	10	Some
SSPM	6	76 @ 702	3.5	7000	3×10^4	30	Full
TES(W)	0.1	50 @ 1550	100	3	1.7×10^6	0.1	Full
TES(W)	0.1	95 @ 1556	100	...	...	0.1	Full
TES(Ha)	0.1	85 @ 850	100	...	...	0.1	Full
TES (Ti)	0.1	81–98 @ 850	100	...	...	1	Full
SNSPD	3	0.7 @ 1550	0.06	10	1.2×10^7	100	None
SNSPD (in cavity)	1.5	57 @ 1550	0.03	...	...	1000	None
Parallel SNSPD	2	2 @ 1300	0.05	0.15	2.7×10^9	1000	Some
STJ	0.4	45 @ 350	2000	...	...	0.01	Full
QD (resonant tunnel diode)	4	12 @ 550	150	0.002	4×10^9	0.25	Full
QDOGFET (field-effect transistor)	4	2 @ 805	10000	150	10	0.05	Full

[a]PNR should be possible, but none has been demonstrated as of yet.

TABLE I. Overview of some SNSPD leading works on different material platforms.

Material	Efficiency/time jitter	Temperature	Wavelength
NbN (Refs. 43 and 45)	92%–98.2%/40–106.1 ps	0.8–2.1 K	1550–1590 nm[a]
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm[b]
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K[c]	1550 nm
MoGe (Ref. 106)	20%/69–187 ps	250 mk–2.5 K	1550 nm
MoRe (Ref. 107)	—/—	9.7 K	—
MoSi (Refs. 108–110)	80%–87% /26–76 ps	0.8–1.2 K[d]	1550 nm
NbRe (Ref. 111)	—/35 ps	2.8 K	500–1550 nm
NbTiN (Ref. 76)	15%–82% /30–70 ps	2.5–6.2 K	400–1550 nm
NbSi (Ref. 112)	—/—	300 mK	1100–1900 nm
TaN (Ref. 113)	—/—	0.6–2 K	600–1700 nm
MgB_2 (Refs. 114–116)	—/—	3–5 K	Visible

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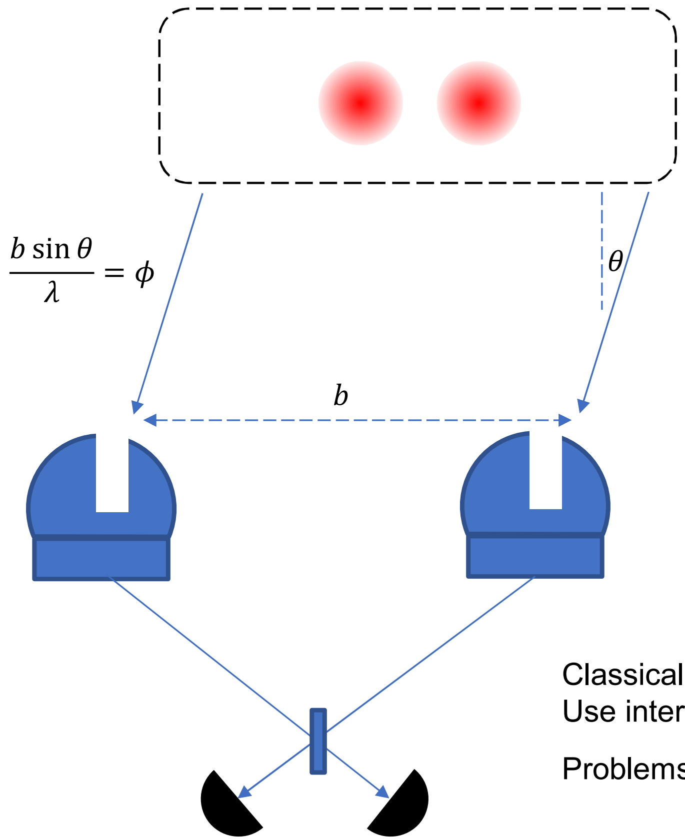
Quantum Telescope



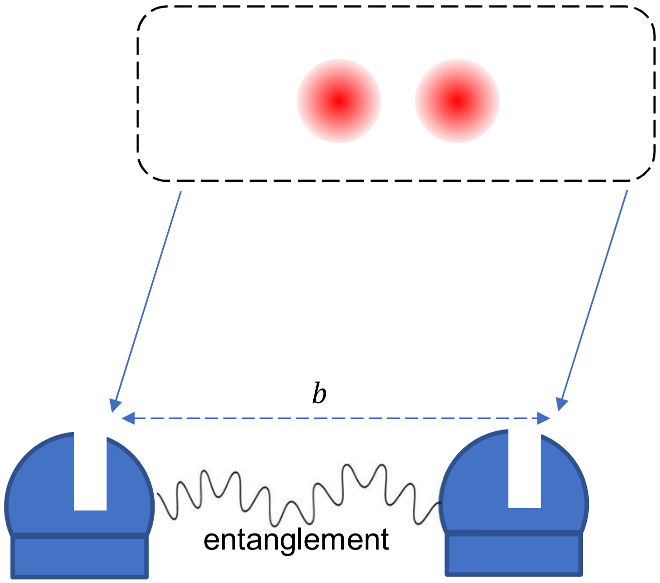
State of single photon coming from distant object

$$|0\rangle_L |1\rangle_R + e^{i\phi} |1\rangle |0\rangle$$

Determing ϕ can precisely locate object

Classical solution: **Direct Detection**
Use interference to find ϕ

Problems: Loss + phase noise limits baseline distance b



Quantum Solution: **Entanglement-based phase measurement**
Use Bell-state measurement to find ϕ

Problems: Need a quantum network!

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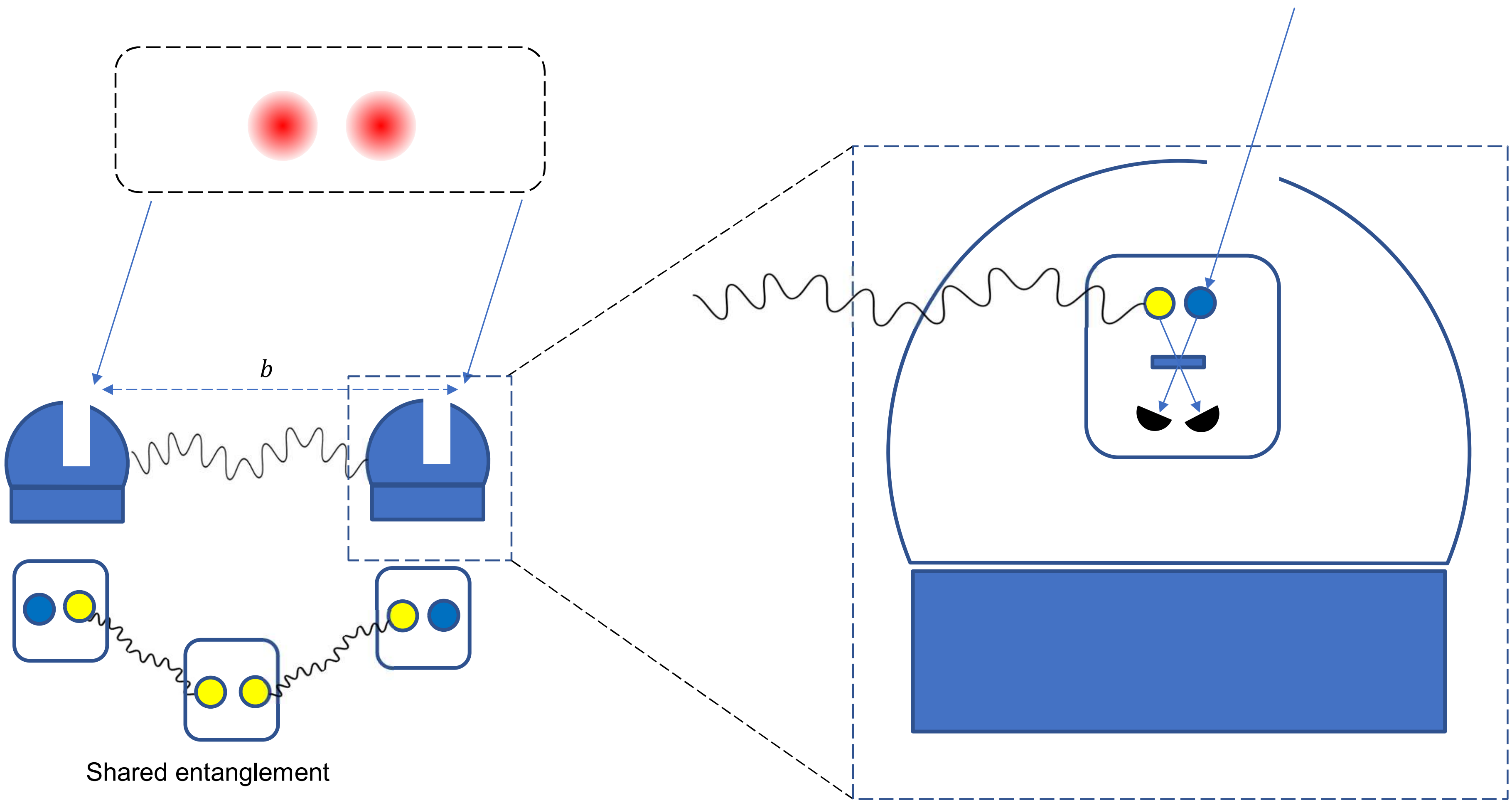

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Review

- Quantum networks distribute entanglement
- Hardware needed to distribute entanglement includes:
  - Quantum Sources
  - Transmission Optics
  - Quantum Memories
  - Detectors
- We did not cover the important **classical** hardware needed
- We introduced one specific application example: Quantum Telescope