Day 1 - quantum photonics

Thursday, July 31, 2025
10:04 AM

Quantum photonics is the study and application of **light (photons)** in **quantum technologies**, where the quantum properties of light are used to perform tasks in computing, communication, and sensing that are not possible with classical technologies.

🔍 Definition:

Quantum photonics is a branch of quantum science and engineering that uses **individual photons** or **entangled photon states** to encode, manipulate, and transmit quantum information.

💡 Key Concepts:

Concept	Description
Photon	A quantum particle of light; carries energy and momentum.
Qubit (Quantum bit)	In quantum photonics, qubits are encoded using properties of photons, such as **polarization**, **path**, **time-bin**, or **orbital angular momentum**.
Superposition	A photon can be in a combination of states at once (like vertical and horizontal polarization).
Entanglement	Two or more photons can be entangled so that their states are strongly correlated, no matter how far apart they are.
Quantum interference	Photons can interfere with themselves or others due to wave-like behavior, which is crucial in quantum computing.
Single-photon sources	Devices that emit one photon at a time for precise quantum operations.
Photon detectors	Specialized detectors used to measure quantum states of photons without disturbing them too much.

⚙️ Applications:

1. **Quantum Computing (Photonic Quantum Computers)**
   - Uses linear optical elements like **beam splitters**, **phase shifters**, and **interferometers**.
   - No need for extreme cooling like superconducting qubits.
   - Example: **Xanadu** (a photonic quantum computing company).
2. **Quantum Communication**
   - **Quantum key distribution (QKD)** for secure communication using entangled photons.
   - **Quantum internet** concepts based on photons transmitting quantum states over optical fibers.
3. **Quantum Sensing and Metrology**
   - Ultra-precise measurements using quantum interference and entanglement (e.g., LIGO for gravitational waves).

📚 Prerequisites to Learn:

- Basics of **quantum mechanics** (superposition, entanglement).
- **Optics and photonics** (polarization, wave behavior of light).
- Quantum information theory (for applications in computing and cryptography).

🔷 Step 1: Classical Photonics & Optics Basics

✅ **Goal**: Understand how light behaves classically before diving into its quantum nature.

Topics:

- Wave-particle duality of light
- Reflection, refraction, diffraction, interference
- Polarization (linear, circular, elliptical)
- Beam splitters, mirrors, lenses, waveplates
- Optical fibers and guided light

📘 Suggested Resource:

- *Optics* by Eugene Hecht (for physics-level detail)
- Khan Academy or Coursera optics courses (for quick visual review)

🔷 Step 2: Quantum Mechanics Refresher

✅ **Goal:** Revisit key quantum principles needed for photonics.

Topics:

- Superposition and measurement
- Uncertainty principle
- Quantum states and operators
- Two-level systems (qubits)
- Quantum entanglement
- Tensor products and Hilbert space

📘 Suggested Resource:

- Griffiths' *Introduction to Quantum Mechanics* (chapters on wave functions, spin, etc.)
- Qiskit Textbook (https://qiskit.org/textbook/) for hands-on quantum computing basics

🔷 Step 3: Introduction to Quantum Optics

✅ **Goal:** Learn how light is treated in quantum mechanics.

Topics:

- Quantization of electromagnetic fields
- Photon as a quantum particle
- Coherent, squeezed, and Fock states
- Creation and annihilation operators
- Optical cavities and laser basics

📘 Suggested Resource:

- *Introductory Quantum Optics* by Gerry & Knight
- MIT OpenCourseWare: Quantum Optics Lectures

🔷 Step 4: Photonic Qubits

✅ **Goal:** Learn how to encode and manipulate quantum information with photons.

Encoding Methods:

- Polarization ($|H\rangle$, $|V\rangle$)
- Path encoding (which slit or fiber)
- Time-bin encoding (early vs late photon)
- Orbital angular momentum (OAM)

📘 Suggested Resource:

- Xanadu's Quantum Codebook: https://codebook.xanadu.ai

🔷 Step 5: Quantum Circuits in Photonics

✅ **Goal:** Understand how quantum gates are implemented with optical components.

Tools & Concepts:

- Beam splitters as Hadamard gates
- Phase shifters
- Interferometers (Mach-Zehnder, Michelson)
- Quantum interference (Hong-Ou-Mandel effect)

📘 Tools:

- Xanadu's **Strawberry Fields** for simulating quantum photonic circuits: https://strawberryfields.ai
- Python and Jupyter for simulations

🔷 Step 6: Applications of Quantum Photonics

✅ **Goal:** See how the concepts are applied in real-world tech.

Applications:

- Photonic quantum computing (e.g., **Xanadu**, **PsiQuantum**)
- Quantum cryptography (BB84 protocol)
- Quantum teleportation using entangled photons
- Quantum-enhanced sensing

🔷 Step 7: Build Projects / Simulate

✅ **Goal:** Practice what you've learned using simulations.

Project Ideas:

- Simulate a photonic beam splitter circuit
- Design BB84 quantum key distribution
- Model Hong-Ou-Mandel interference

📘 Tools:

- Python + Strawberry Fields (photonic circuits)
- Python + Qiskit (general quantum circuits)

📅 Quantum Photonics Course Plan (4 Hours per Day)

🔢 Total Time Required: ~120 hours

At 4 hrs/day → ~30 days total (1 month)

✅ Week 1 (28 hours)

📘 **Step 1: Classical Photonics & Optics — *15 hours***

- Day 1–2: Wave optics, interference, diffraction
- Day 3: Polarization, waveplates
- Day 4: Optical fibers, beam splitters, mirrors
- Day 5: Practical components (lasers, detectors)

📘 **Step 2: Quantum Mechanics Refresher — *13 hours***

- Day 6: Superposition, measurement
- Day 7: Qubits, entanglement basics

✅ Week 2 (28 hours)

📘 **Step 2 (contd.): Quantum Mechanics — *7 hours***

- Day 1: Spin-½ systems, tensor products, operators

📘 **Step 3: Quantum Optics — *21 hours***

- Day 2–3: Quantization of EM field, photon states
- Day 4: Coherent/Fock states, ladder operators
- Day 5–7: Optical cavities, laser basics, squeezed states

✅ Week 3 (28 hours)

📘 **Step 4: Photonic Qubits — *10 hours***

- Day 1–2: Encoding qubits (polarization, path, time-bin)
- Day 3: Multi-qubit photon systems

📘 **Step 5: Quantum Circuits in Photonics — *18 hours***

- Day 4: Beam splitters as gates
- Day 5: Phase shifters, interferometers
- Day 6: Quantum interference (Hong-Ou-Mandel)
- Day 7: Full photonic gate examples

✅ Week 4 (36 hours)

📘 **Step 6: Applications — *10 hours***

- Day 1–2: Quantum communication (BB84, QKD)
- Day 3: Photonic quantum computing
- Day 4: Sensing, teleportation

📘 **Step 7: Projects/Simulations — *26 hours***

- Day 5–7:
    - Build & simulate simple photonic circuits
    - Hong-Ou-Mandel interference experiment in code
    - Build a QKD simulation
    - Try a basic circuit in **Strawberry Fields**

📘 Day 1: Classical Photonics – Wave Nature of Light

🎯 Learning Objectives:

By the end of today's session (4 hours), you will:

- Understand light as a wave
- Learn about interference and diffraction
- Know how superposition leads to patterns critical in quantum photonics

🧠 1. Light as an Electromagnetic Wave (30 mins)

Light is an **electromagnetic wave** consisting of oscillating electric ($\mathbf{E}$) and magnetic ($\mathbf{B}$) fields.

➤ Maxwell's Wave Equation:

$$\nabla^2\mathbf{E} = \mu_0\varepsilon_0\frac{\partial^2\mathbf{E}}{\partial t^2}$$

Solution:

$$\mathbf{E}(x,t) = E_0\cos(kx-\omega t)$$

- $k = 2\pi/\lambda$: wave number
- $\omega = 2\pi f$: angular frequency
- $c = \lambda f$: speed of light

✅ **Key idea:** Light behaves like a wave with properties of **wavelength**, **frequency**, and **amplitude**.

🌈 2. Superposition Principle (30 mins)

The **total wave** is the sum of individual waves.

$$E_{\text{total}} = E_1 + E_2$$

- If peaks align → **Constructive Interference**
- If peaks cancel → **Destructive Interference**

Used in:

- Interferometers
- Double-slit experiments
- Quantum gates with photons

🌊 3. Interference (1 hour)

🔷 Young's Double-Slit Experiment:

A single light source passes through two slits. You observe bright and dark fringes on a screen.

$$\Delta L = d \sin\theta$$

$$\text{Constructive: } d\sin\theta = m\lambda \quad (m = 0, 1, 2\ldots)$$

$$\text{Destructive: } d\sin\theta = (m + 1/2)\lambda$$

✅ **Takeaway:** The interference pattern comes from **path difference** – critical in **quantum interference** with single photons too.

🔍 4. Diffraction (30 mins)

When light encounters a slit or obstacle, it **bends** and **spreads** out.

Single-slit Diffraction:

$$a \sin\theta = m\lambda$$

- a: slit width
- Central maximum is the brightest

✅ **Takeaway:** Diffraction explains light's wave nature and is foundational to **quantum optics experiments**.

📷 5. Real Devices (30 mins)

Device	Purpose
Beam Splitter	Splits light into two paths (used as quantum gates)
Mirrors	Reflects and directs light
Lenses	Focuses light beams
Gratings	Splits light into wavelengths (spectrum)

Day 2

Thursday, July 31, 2025

10:31 AM

📘 Day 2: Polarization of Light

🎯 Learning Objectives:

By the end of this session (4 hours), you will:

- Understand the concept and types of polarization
- Learn how polarization is used to encode qubits
- Familiarize with polarizers, waveplates, and their use in quantum circuits

🔶 1. What is Polarization? (45 mins)

Light is a **transverse wave**—its **electric field** oscillates perpendicular to the direction of travel.

Polarization refers to the **direction of this oscillation**.

Types of Polarization:

Type	Electric Field Behavior
Linear	Oscillates in a fixed direction (horizontal, vertical)
Circular	Rotates uniformly (clockwise or counterclockwise)
Elliptical	General case – rotating but uneven

Representation:

- Linear Horizontal → $|H\rangle$
- Linear Vertical → $|V\rangle$
- Diagonal (45°) → $|+\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$
- Circular → $|R\rangle, |L\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm i|V\rangle)$

✅ These states map directly to **quantum photonic qubits.**

🧪 2. Polarizers and Malus' Law (30 mins)

Polarizer:

- Allows only a specific polarization to pass
- Ideal polarizer removes all components orthogonal to its axis

Malus' Law:

$$I = I_0 \cos^2 \theta$$

- I_0: initial intensity
- θ: angle between light's polarization and polarizer's axis

✅ You can **control and measure photon polarization** using polarizers — essential for **state preparation and measurement.**

🔁 3. Waveplates (Retarders) (1 hour)

Waveplates shift the phase between E_x and E_y components of light.

Type	Function
Half-wave plate (HWP)	Rotates linear polarization by angle 2θ
Quarter-wave plate (QWP)	Converts linear ↔ circular polarization

✅ **In quantum gates:**

- HWPs are used to perform **bit-flip operations** (X-gates).
- QWPs help create and measure **superposition or circularly polarized states.**

🎯 4. Polarization as Qubit Basis (45 mins)

Encoding a Qubit:

$$|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

- $|H\rangle \leftrightarrow$ logical 0
- $|V\rangle \leftrightarrow$ logical 1
- Polarization state is a **physical realization of a qubit**

Superposition Example:

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

✅ **Measuring in different polarization bases** gives **probabilities** related to qubit outcomes.

🧰 5. Real-World Quantum Applications (30 mins)

- **BB84 Protocol** uses polarization (H, V, +45°, -45°) for **quantum key distribution**
- **Quantum teleportation** and **Bell tests** often use polarization-entangled photons
- Polarization control is critical in **quantum photonic circuits**

📝 6. Practice Exercises (Optional – 30 mins)

1. Light of intensity I_0 is linearly polarized. What is transmitted intensity through a polarizer at 60°?
2. What is the polarization state after passing through a HWP at 22.5°?
3. Represent circular polarization in terms of |H⟩ and |V⟩.

✅ Summary (Quick Recap)

- **Polarization** describes the direction of light's electric field.
- It is the **preferred basis for photonic qubits**.
- Devices like **polarizers** and **waveplates** are used to manipulate and measure quantum states.
- You now understand how **classical polarization maps to quantum states**.

Day 3

Thursday, July 31, 2025
10:33 AM

📘 Day 3: Optical Components – Beam Splitters, Interferometers, and Lenses

🎯 Learning Objectives:

By the end of this 4-hour session, you'll:

- Understand how basic optical components work
- See how they correspond to **quantum operations**
- Learn about interferometers like **Mach–Zehnder** that demonstrate quantum interference

🔷 1. Beam Splitters (BS) – *1 hour*

A **beam splitter** divides an incoming beam into two paths.

🔶 Types:

- **50:50 Beam Splitter:** Reflects 50% and transmits 50%
- **Polarizing Beam Splitter (PBS):** Separates light based on polarization (H → transmits, V → reflects)

🔶 Quantum Description:

For input modes a and b, output modes c and d:

$$\hat{c} = \frac{1}{\sqrt{2}}(\hat{a} + i\hat{b}), \quad \hat{d} = \frac{1}{\sqrt{2}}(i\hat{a} + \hat{b})$$

🔶 As a Quantum Gate:

Acts like a **Hadamard gate** for path-encoded qubits:

$$|0\rangle \to \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

✅ **Key Role in Quantum Circuits:** Controls interference, entanglement, and superposition of photons.

🔷 2. Interferometers – *1.5 hours*

Used to **split and recombine beams**, creating interference patterns. In quantum optics, they're **gates or logic circuits.**

🔶 Mach–Zehnder Interferometer (MZI):

Structure:

- Input → Beam Splitter 1 → Two paths → Beam Splitter 2 → Output

With single photons:

- Shows interference **without classical explanation**
- Basis for demonstrating **quantum superposition**

🔶 Phase Shifters:

Introduce a phase difference between paths:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$$

Phase shift controls the **output probabilities** at detectors.

✅ MZI = Beam Splitter → Phase → Beam Splitter
✅ You'll simulate this in later projects!

🔷 3. Mirrors and Lenses – *30 mins*

🔶 Mirrors:

- Change direction of beams
- Maintain polarization in many cases
- Essential for building optical paths

🔶 Lenses:

- Focus or collimate light
- Used to couple photons into **optical fibers** or **detectors**

While **not quantum elements**, they're essential for building and aligning **photonic quantum experiments.**

🔷 4. Real Quantum Circuit: Hong–Ou–Mandel Interference

Setup:

- Two identical photons enter **opposite ports** of a 50:50 beam splitter

Observation:

- **Classically**: Expect 50/50 detection
- **Quantumly**: Photons "bunch" → Always exit **together** in the same port
- No coincidence counts!

✅ **HOM dip** in detector correlation is proof of **quantum interference**

This is the "**Hello World**" of quantum photonics experiments!

🧰 5. Component Summary Table – (15 mins)

Component	Function	Quantum Role
Beam Splitter	Split/merge paths	Superposition / interference
PBS	Polarization-based splitting	Measurement / qubit separation
Phase Shifter	Adds phase to beam	Quantum phase gate
Interferometer	Recombine paths	Logic gate, circuit framework
Mirror	Redirects beam	Alignment in quantum circuit
Lens	Focuses light	Coupling and detection

📝 Practice & Reflection (Optional – 30 mins)

1. What happens if one path in a Mach–Zehnder is blocked?
2. Sketch or describe how a Hadamard gate could be implemented using BS and phase shifters.
3. What does a PBS do when diagonally polarized light enters?

✅ Summary

- Beam splitters and phase shifters form the **core of photonic quantum gates**
- Interferometers like MZI help visualize **quantum interference**
- HOM interference reveals **purely quantum behavior of photons**
- Understanding these tools bridges classical optics with **quantum circuit design**

Day 4

Thursday, July 31, 2025

11:29 AM

📘 Day 4: Quantum Mechanics Refresher – Superposition, Measurement, and Qubits

🎯 Learning Objectives:

By the end of this 4-hour session, you'll:

- Understand the foundational concepts of quantum mechanics used in photonics
- Learn what a qubit is and how it differs from a classical bit
- Explore quantum measurement and probabilities
- Prepare for encoding quantum information in photons

🔷 1. Classical Bit vs Quantum Qubit (30 mins)

Classical Bit	Quantum Qubit
Either 0 or 1	A superposition of 0 and 1
Deterministic	Probabilistic outcomes
Copied easily	Cannot be copied (no-cloning)

A **qubit** is represented as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $\alpha, \beta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 = 1$

🔷 2. Superposition (1 hour)

A qubit can exist in a **linear combination** of states:

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

This is **not** being "in both states"—it's being in **a unique state** that has a probability amplitude for each outcome.

➤ Example in Quantum Photonics:

A **beam splitter** acts on a photon like a **Hadamard gate**, creating superposition in path or polarization.

✅ This is the basis for all **quantum interference** and **quantum gates**.

🔷 3. Measurement and Probability (45 mins)

When you **measure** a qubit:

- You get **|0⟩** with probability $|\alpha|^2$
- You get **|1⟩** with probability $|\beta|^2$

Measurement **collapses the superposition** to one of the basis states.

Quantum Photonics View:

- Use **polarizers**, **detectors**, or **interferometers** to measure polarization or path
- You only get one outcome per run, so multiple repetitions are used to build statistics

🔷 4. Qubit States on the Bloch Sphere (45 mins)

Visualize a single qubit as a point on a 3D unit sphere:

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

- θ: angle from vertical (|0⟩)
- φ: phase difference

🔷 5. Quantum Gates Refresher (30 mins)

These are **unitary operations** that rotate or flip qubits:

Gate	Matrix	Operation
X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	Bit flip
Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	Phase flip
H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	Creates superposition

✅ In photonic circuits:

- Beam splitter = H gate
- Phase shifter = Z gate
- Polarizer or HWP = X/Z depending on axis

🔷 6. Practice Problems / Thought Experiments (Optional – 30 mins)

1. If a qubit is in state $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, what is the probability of measuring $|0\rangle$?
2. What gate turns $|0\rangle$ into $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$?
3. Why can't we copy an arbitrary quantum state?

✅ Summary

- Qubits are **superpositions** of $|0\rangle$ and $|1\rangle$
- Measurement **collapses** the state probabilistically
- Quantum gates **manipulate** qubits like rotations on the Bloch sphere
- In **quantum photonics**, all these operations are **physically implemented** using optical components (BS, phase shifters, polarizers)

Day 5

Thursday, July 31, 2025
11:31 AM

📘 Day 5: Quantum Entanglement and Multi-Photon Systems

🎯 Learning Objectives:

By the end of this session, you'll:

- Understand what quantum entanglement is
- Learn how it manifests in photonic systems
- See how entangled photon pairs are generated and used
- Study examples like Bell states and Bell tests

🔷 1. What is Entanglement? (45 mins)

Entanglement is a uniquely quantum phenomenon where **two or more particles** share a state such that **measuring one affects the other**, no matter how far apart they are.

Example:

The Bell state:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

- If Alice measures **0**, Bob will **always** measure 0.
- If Alice measures **1**, Bob will **always** measure 1.

But each outcome is **individually random**.
The correlation is what's quantum.

🔷 2. Bell States – *1 hour*

There are four maximally entangled **Bell states**:

$$
\begin{aligned}
|\Phi^+\rangle &= \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \\
|\Phi^-\rangle &= \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) \\
|\Psi^+\rangle &= \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \\
|\Psi^-\rangle &= \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)
\end{aligned}
$$

Each has unique correlation properties. These are the **building blocks of quantum communication** and entangled photon experiments.

🔷 3. Entangled Photons in Quantum Photonics – *1 hour*

In photonics, entangled states are typically created using:

Spontaneous Parametric Down-Conversion (SPDC):

- A nonlinear crystal (like BBO) is pumped with a laser
- Occasionally, one high-energy photon **splits into two lower-energy photons**
- These **daughter photons** are entangled in:
  - **Polarization**
  - **Momentum**
  - **Time-bin**

🧪 **Lab Setup Includes:**

- Nonlinear crystal (e.g., BBO)
- Pump laser
- Beam splitters and waveplates
- Coincidence detectors

✅ These systems are used in:

- Bell test experiments
- Quantum key distribution
- Quantum teleportation

🔷 4. Bell Test and CHSH Inequality – *45 mins*

Bell's theorem proves quantum mechanics makes predictions **that no local hidden variable theory can**.

CHSH Inequality:

A statistical bound:

$$|S| \leq 2 \quad \text{(Classical)}$$
$$|S| \leq 2\sqrt{2} \quad \text{(Quantum)}$$

Violation of the classical bound proves the presence of quantum entanglement.

✅ **Quantum photonic circuits** using entangled photons have repeatedly **violated Bell inequalities**, confirming quantum nonlocality.

🔷 5. Real-World Quantum Photonics Applications Using Entanglement (30 mins)

Application	Description
Quantum Teleportation	Transferring quantum states using entangled photons
Quantum Key Distribution	Secure encryption using entangled states (e.g., E91 protocol)
Quantum Repeater	Entanglement swapping for long-distance communication
Quantum Sensors	Ultra-precise measurements using entangled photon pairs

📝 Practice Questions / Thought Experiments (Optional – 30 mins)

1. Explain why the state $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ is entangled.
2. If you measure one photon in $|\Psi^+\rangle$ and get $|0\rangle$, what will you measure for the other?
3. Why is SPDC probabilistic, and what limits its scalability for quantum computers?

✅ Summary

- Entanglement links quantum particles in a way **classical systems cannot replicate**
- In photonics, **entangled photon pairs** are generated using **nonlinear crystals and lasers**
- **Bell states** form the basis of **quantum communication protocols**
- **Bell tests** demonstrate the failure of classical realism and the correctness of quantum theory

Day 6

Thursday, July 31, 2025
11:33 AM

📘 Day 6: Quantum Optics – Quantized Light and Photon States

🎯 Learning Objectives:

By the end of this session (4 hours), you'll:

- Understand how the electromagnetic field is quantized
- Learn about Fock states, coherent states, and their physical meanings
- See how these states relate to lasers, single-photon sources, and quantum computation
- Get familiar with creation/annihilation operators

🔷 1. Quantization of the Electromagnetic Field – *1 hour*

In quantum optics, the electromagnetic (EM) field is treated as a **quantum harmonic oscillator** at each mode (frequency + polarization).

Classical Field:

$$E(t) = E_0 \cos(\omega t + \phi)$$

Quantum Field:

Use operators to describe quantized energy levels:

- $\hat{a}^\dagger$: **Creation operator** – adds a photon
- $\hat{a}$: **Annihilation operator** – removes a photon

$$\hat{H} = \hbar\omega \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right)$$

- Each mode has **discrete photon energy levels:** $n\hbar\omega$
- Photon number = eigenvalue of $\hat{n} = \hat{a}^\dagger \hat{a}$

✅ This is the foundation for modeling **quantum light**.

🔷 2. Fock States (Number States) – *45 mins*

Fock state $|n\rangle$ = **n photons in a given mode**

State	Meaning
(	0\rangle)
(	1\rangle)
(	2\rangle)

Operators act as:

$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle, \quad \hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$

✅ Used in **single-photon sources**, **quantum computation**, and **entanglement**.

🔷 3. Coherent States – *45 mins*

Laser light is best described by a **coherent state** $|\alpha\rangle$, not a Fock state.

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Properties:

- Has **Poisson distribution** of photon numbers
- Closest to classical light
- Maintains phase relationship

✅ Lasers emit coherent states → widely used in **interferometry and optical quantum gates.**

🔷 4. Squeezed States (Intro) – *30 mins*

Squeezed states reduce quantum uncertainty in one variable (like phase or amplitude) below the vacuum level.

- Used in **quantum-enhanced sensors** (e.g., LIGO)
- Beyond today's scope, but worth noting as **non-classical light**

🔷 5. Single-Photon Sources & Detectors – *45 mins*

Single-Photon Sources:

- Heralded SPDC sources
- Quantum dots
- Nitrogen-vacancy centers

Single-Photon Detectors:

- Avalanche photodiodes (APDs)
- Superconducting nanowire detectors (SNSPDs)

✅ These devices are essential in **quantum experiments, cryptography, and computing**.

📝 Practice Exercises (Optional – 30 mins)

1. Show that $\hat{n}|\alpha\rangle \neq n|\alpha\rangle$. What does that imply?
2. If a beam splitter acts on $|1\rangle \otimes |0\rangle$, what are the possible output photon numbers?
3. Which state is more "classical": $|1\rangle$ or $|\alpha\rangle$? Why?

✅ Summary

- The EM field is **quantized**, leading to discrete photon states
- **Fock states:** Fixed number of photons (used in quantum computing)
- **Coherent states:** Laser-like classical light with quantum features
- **Creation/annihilation operators** define photon behavior mathematically
- These quantum light models form the backbone of **quantum photonic simulations**

Day 7

Thursday, July 31, 2025
11:36 AM

📘 Day 7: Quantum Interference – Hong–Ou–Mandel Effect & Two-Photon Phenomena

🎯 Learning Objectives:

By the end of this session, you will:

- Understand what quantum interference is and how it differs from classical interference
- Explore the **Hong–Ou–Mandel (HOM) effect**
- Analyze how HOM interference is used to test photon indistinguishability
- Simulate or visualize this effect for deeper insight

🔷 1. Classical vs Quantum Interference – *30 mins*

🔶 Classical Interference:

- Based on **wave amplitude** addition (like in double-slit)
- Works with continuous wavefronts

🔶 Quantum Interference:

- Occurs at the **probability amplitude level**
- Only visible when photons are **indistinguishable**
- Does **not** arise from intensity patterns, but from **destructive addition of probability amplitudes**

✅ This is key in **multi-photon quantum circuits** like entanglement swapping or quantum gates.

🔷 2. Hong–Ou–Mandel (HOM) Effect – *1 hour*

🧪 Setup:

- Two **identical photons** enter a 50:50 beam splitter from opposite sides
- Classically: 50% chance both exit different outputs
- Quantum mechanically: **They always leave together from the same output port**

HOM State Evolution:

Input state:

$$|1\rangle_A \otimes |1\rangle_B$$

After 50:50 beam splitter:

$$\frac{1}{\sqrt{2}}(\hat{a}^\dagger + i\hat{b}^\dagger)(i\hat{a}^\dagger + \hat{b}^\dagger)|0\rangle = \frac{i}{\sqrt{2}}(|2\rangle_C|0\rangle_D + |0\rangle_C|2\rangle_D)$$

📉 **Result:**

- No $|1\rangle|1\rangle$ term → **no coincidence counts**
- Photons "bunch" in the same mode → **quantum interference**

HOM Dip:

When delay = 0 (photons are indistinguishable), the **coincidence rate drops** to zero. This is called the **HOM dip**.

🔷 3. Significance of HOM Effect – *30 mins*

Use Case	Description
Photon indistinguishability test	If no HOM dip → photons not identical
Entanglement protocols	Used in **entanglement swapping**
Photonic quantum gates	Basis for logic gates like CNOT

✅ HOM interference is a **crucial building block** in scalable quantum photonic systems.

🔷 4. Visualizing with Simulation (Optional) –

If you'd like to simulate this (Python):

```python
from strawberryfields import Program
from strawberryfields.ops import Fock, BSgate
import strawberryfields as sf

eng = sf.Engine("fock", backend_options={"cutoff_dim": 3})
prog = Program(2)

with prog.context as q:
    Fock(1) | q[0]
    Fock(1) | q[1]
    BSgate(np.pi/4, 0) | (q[0], q[1])
```

```python
results = eng.run(prog)
state = results.state
print(state.fock_prob([2,0]), state.fock_prob([1,1]), state.fock_prob([0,2]))
```

✅ You'll see that the $[1, 1]$ outcome probability is **0** → clear HOM interference.

🔷 5. Extensions: Multi-Photon Interference – *45 mins*

As you scale up to more photons:

- You get **boson sampling**, where photon paths interfere in complex ways
- Useful in **quantum supremacy** experiments (e.g., **Xanadu**, **Google**)

Tools:

- **Interferometers (e.g., MZI arrays)**
- **Time-bin encodings**
- **Photon number-resolving detectors**

✅ Multi-photon interference is essential for **quantum simulation and computation.**

📝 Practice & Thought Experiments (Optional – 30 mins)

1. Why must photons be identical (same spectrum, polarization, etc.) to see HOM dip?
2. What happens if the photons arrive at different times?
3. Can you simulate a beam splitter acting on $|1\rangle \otimes |0\rangle$ and predict the output?

✅ Summary

- **Quantum interference** is not about light intensity, but **probability amplitudes**
- The **Hong–Ou–Mandel effect** shows **two-photon interference**, not explainable classically
- HOM dip proves **indistinguishability** of photons
- It's widely used in **quantum photonic circuits**, teleportation, gates, and entanglement operations

Day 8

Thursday, July 31, 2025

11:39 AM

📘 Day 8: Encoding Qubits – Polarization, Path, Time-Bin, and Orbital Angular Momentum (OAM)

🎯 Learning Objectives:

By the end of this session, you will:

- Understand the various ways qubits can be encoded using photons
- Learn the pros and cons of each encoding method
- Prepare for hybrid encoding and multi-qubit photonic systems

🔷 1. Polarization Encoding – *45 mins*

Qubit Basis:

- $|H\rangle = |0\rangle$: Horizontal polarization
- $|V\rangle = |1\rangle$: Vertical polarization

You can also define diagonal/anti-diagonal bases:

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

Devices:

- **Waveplates (QWP, HWP)**: Manipulate polarization
- **PBS (Polarizing Beam Splitters)**: Separate |H⟩ and |V⟩
- **Single-photon detectors**

✅ **Widely used in:**

- Quantum key distribution (BB84)
- Bell state generation
- Simple photonic circuits

✔️ **Pros:** Simple to implement

✖️ **Cons:** Limited scalability (only 2D space)

🔷 2. Path Encoding – *1 hour*

Qubit Basis:

- Photon in **path A** → $|0\rangle$
- Photon in **path B** → $|1\rangle$

This is also called **dual-rail encoding**.

Components:

- Beam splitters → Create superpositions between paths
- Phase shifters → Add phase to one path
- Interferometers (e.g. MZI) → Combine or measure interference

✅ Used in:

- Logic gates (e.g., CNOT)
- Quantum computing circuits

✔️ **Pros:** Compatible with integrated photonics
✖️ **Cons:** Requires stable path length (sensitive to noise)

🔷 3. Time-Bin Encoding – *45 mins*

Qubit Basis:

- Photon arrives at **early time (t_0)** → $|0\rangle$
- Photon arrives at **late time (t_1)** → $|1\rangle$

Used in **fiber-optic communication** and **long-distance entanglement**.

Implementation:

- Use **unbalanced interferometers** to create or measure time-bin qubits
- Detectors must have **high time resolution**

✅ Used in:

- Quantum repeaters
- Satellite-based quantum links

✔️ **Pros:** Robust to polarization drift in fibers
✖️ **Cons:** Harder to manipulate (requires time-resolved detectors)

🔷 4. Orbital Angular Momentum (OAM) Encoding – *30 mins*

Photons can carry **twisting phase fronts**, giving them **quantized angular momentum**:

$$|l\rangle = \text{Photon with OAM of } l\hbar$$

Qubit Encoding:

- Use two OAM values to define $|0\rangle$ and $|1\rangle$

You can also create **qudits** (d-level systems) using multiple OAM modes.

Devices:

- Spatial light modulators (SLMs)
- Spiral phase plates
- q-plates

✅ Used in:

- High-dimensional quantum communication
- Multiplexing quantum data

✔️ **Pros:** Scalable to high-dimensional systems
✖️ **Cons:** Needs precise beam shaping and alignment

🔷 5. Hybrid Encodings (Bonus) – *30 mins*

Photons can be encoded in **multiple degrees of freedom simultaneously**:

- **Polarization + Path**
- **Time-bin + Frequency**
- **OAM + Polarization**

This enables:

- **Hyper-entanglement** (multiple entanglements in one pair)
- **Dense information encoding**
- **Error correction**

✅ Important for **scalable quantum photonic computing**.

📝 Practice / Thought Questions (Optional – 30 mins)

1. How would you prepare a qubit using time-bin encoding?
2. How can a Mach–Zehnder interferometer be used to measure a path-encoded qubit?
3. Which encoding method is most robust for quantum communication over long distances?

✅ Summary

Encoding Type	Pros	Challenges
Polarization	Easy to manipulate and measure	Limited to 2D space
Path (Dual-rail)	Compatible with integrated photonics	Requires interferometric stability
Time-bin	Fiber-compatible, good for QKD	Requires precise timing and fast detectors
OAM	High-dimensional encoding	Needs precise spatial control

You now know how quantum information is **physically embedded in light** – the heart of **quantum photonic circuits**!

Day 9

Thursday, July 31, 2025
11:43 AM

📘 Day 9: Photonic Quantum Gates and Circuits

🎯 Learning Objectives:

By the end of this session, you'll:

- Understand how **quantum gates** operate on photonic qubits
- Learn how to implement **single- and two-qubit gates** using optical components
- Explore **photonic circuit models** for quantum computation
- Study real examples: **Hadamard, Pauli, CNOT, CZ**, etc.

🔷 1. Quantum Gates Refresher – *30 mins*

In general, **quantum gates are unitary operations** on qubits:

$$U^\dagger U = I$$

Common Single-Qubit Gates:

Gate	Matrix	Photonic Equivalent
X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	Half-wave plate at 45°
Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	Phase shifter
H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	50:50 beam splitter or HWP+QWP combo

✅ In photonics, these gates are implemented using **beam splitters, phase shifters, and waveplates.**

🔷 2. Path-Encoded Logic Gates – *45 mins*

In **dual-rail encoding**, a qubit is represented by **presence of a photon in one of two paths.**

Example: Hadamard Gate using Beam Splitter

$$|1\rangle_A|0\rangle_B \to \frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B)$$

→ A **50:50 beam splitter** acts like a Hadamard gate:

- Superposes the path
- Creates interference if followed by another BS or detector

✅ Add a **phase shifter** in one path → get **arbitrary single-qubit rotations.**

🔷 3. Two-Qubit Gates – CNOT and CZ – *1 hour*

Two-qubit gates require **interaction**, which is hard with photons (they don't naturally interact). But clever setups can **simulate interaction** using:

🔶 Controlled-Z (CZ) Gate:

- Using entangled photons + post-selection
- Acts like:

$$|ab\rangle \to (-1)^{a\cdot b}|ab\rangle$$

🔶 CNOT Gate:

- Can be constructed using:
    - **Polarization control + interferometers**
    - **Nonlinear crystals (KLM scheme)**
    - **Measurement-based gates**

KLM scheme (Knill–Laflamme–Milburn):

- Uses linear optics + ancilla photons + post-selection to implement CNOT
- Demonstrates that **linear optics is sufficient for universal quantum computing**

✅ These gates are probabilistic but scalable using **measurement + feedforward.**

🔷 4. Example: Mach–Zehnder Interferometer as Quantum Circuit – *30 mins*

Setup:

- Input: Single photon into MZI
- Components: 2 beam splitters + phase shifter

Effect:

- Can create superposition → apply phase → interfere at second BS
- Behaves like a full **single-qubit rotation** gate

$$U_{\text{MZI}} = R_z(\phi) H R_z(\theta) H$$

✅ Used as a **programmable unit cell** in many **photonic processors.**

🔷 5. Universal Photonic Circuits – *45 mins*

Using:

- **Reconfigurable interferometers**
- **Tunable phase shifters**
- **Integrated photonic chips (e.g., silica or silicon photonics)**

Any **unitary operation U** can be decomposed into a series of **beam splitters and phase shifters** (Reck or Clements decomposition algorithms).

✅ This is how **Xanadu's Strawberry Fields**, **PsiQuantum**, and others design real quantum photonic

🔷 6. Measurement in Photonic Circuits – *30 mins*

At the end of circuits, **photon detectors** (like APDs or SNSPDs) measure outcomes:

- Polarization basis → use PBS + detector
- Path basis → detector at each path
- Time-bin → time-resolving detector

✅ **Photon detection** = **qubit measurement** in photonic computing.

📝 Practice / Thought Exercises (Optional – 30 mins)

1. Show that a 50:50 beam splitter performs a Hadamard-like operation.
2. Describe how you'd build a Z gate using a phase shifter.
3. What's the role of post-selection in building a CNOT gate with photons?

✅ Summary

- **Single-photon gates** use beam splitters, phase shifters, and waveplates
- **Two-qubit gates** require **measurement-based schemes or entanglement**
- **Mach–Zehnder interferometers** form universal gate units
- Modern photonic chips allow full quantum gate sets using **linear optics and detection**

Day 10

Thursday, July 31, 2025

11:48 AM

📘 Day 10: Integrated Photonics and Photonic Quantum Processors

🎯 Learning Objectives:

By the end of this session, you will:

- Understand what integrated photonics is
- Learn how photonic quantum circuits are implemented on chips
- Explore leading technologies and platforms
- Understand programmability and scalability in photonic processors

🔷 1. What is Integrated Photonics? – *30 mins*

Integrated photonics means embedding optical components (beam splitters, phase shifters, interferometers) on a single chip using materials like:

- **Silicon photonics**
- **Silica-on-silicon**
- **Lithium niobate**
- **Indium phosphide**

✅ Benefits:

- Compact and scalable
- Low-loss and phase-stable
- Compatible with CMOS fabrication

🔷 2. Components of a Photonic Chip – *45 mins*

Component	Role
Waveguides	Guide photons like wires
Beam splitters	Create superpositions or MZIs
Phase shifters	Apply rotations (Z or arbitrary axes)
Interferometers	Implement logic and gates
Detectors	Measure outcomes (on/off or number)

> 🖊 These elements are lithographically patterned like transistors on an electronic chip.

🔷 3. Universal Photonic Circuits – *1 hour*

Any **unitary operation** U on n modes can be decomposed into a **network of beam splitters + phase shifters** using:

- **Reck decomposition** (triangular layout)
- **Clements decomposition** (rectangular layout)

Example:

A **programmable 4-mode interferometer** can perform:

- Arbitrary 2-qubit logic
- Entanglement creation
- Quantum walks

✅ This enables **universal linear optical quantum computing** (LOQC).

🔷 4. Programmable Photonic Quantum Processors – *45 mins*

Example Platforms:

- **Xanadu's Borealis** (time-bin + loop architecture)
- **PsiQuantum** (silicon photonics + fusion-based model)
- **ORCA**, **QuiX Quantum**, **Anyon Systems**

These platforms allow:

- Real-time configuration of gates
- Running quantum algorithms (e.g. Gaussian boson sampling)
- Integration with quantum-classical hybrid computing

🔷 5. Challenges and Engineering Solutions – *30 mins*

Challenge	Solution
Loss in waveguides	Use low-loss materials & design
Phase drift	Use thermo-optic/electro-optic tuning
Photon source scaling	Use multiplexing & quantum dots
On-chip detection	Integrate SNSPDs or avalanche diodes

✅ Future goal: Fully integrated **quantum photonic CPU**

🔷 6. Real-World Applications – *30 mins*

Application	Description
Boson sampling	Demonstrates quantum advantage using many indistinguishable photons
Quantum simulation	Model complex molecules or materials using Gaussian states
Quantum machine learning	Use optical interference + measurement for kernel-based learning
Secure communication	Chip-based QKD systems over fiber networks

📝 Practice / Thought Questions (Optional – 30 mins)

1. What are the advantages of integrated photonics over bulk optics?
2. Describe how a 3-mode photonic chip could be used to simulate a molecule.
3. Why is phase stability easier to maintain in integrated photonics?

✅ Summary

- Integrated photonics enables **scalable, low-loss, and programmable** quantum circuits
- Core components: waveguides, phase shifters, beam splitters, detectors
- Full unitary transformations are realizable using **interferometer networks**
- Major companies are developing **photonic quantum processors** using this technology

Day 11

Thursday, July 31, 2025

11:51 AM

📅 Day 11: Quantum Communication with Photons – Protocols and Security

🎯 Goal:

Understand how photons are used for secure transmission of quantum information.

🔷 1. Why Use Photons?

- **Speed of light** → ideal for long-distance communication
- **Low interaction** → less decoherence
- **Can be encoded in polarization, time-bin, path, or frequency**

🔷 2. Core Quantum Communication Protocols

🔶 BB84 (1984, Bennett & Brassard)

- Uses **polarization states** in two bases:
  - Z-basis: $|0\rangle$ = horizontal (H), $|1\rangle$ = vertical (V)
  - X-basis: $|+\rangle$ = diagonal, $|-\rangle$ = anti-diagonal
- Sender (Alice) and receiver (Bob) choose random bases.
- After transmission, they publicly compare bases (not bits) and keep matching ones.
- Any eavesdropper (Eve) introduces **errors** → detectable!

🔶 E91 (1991, Ekert)

- Uses **entangled photon pairs**
- Bell test ensures security: violation → photons were entangled → no eavesdropping
- Used in **device-independent QKD**

🔷 3. Other Concepts

🔶 Quantum Teleportation

- Transfers quantum state using:
  - One entangled photon pair
  - Two classical bits (from Bell measurement)
- Doesn't transmit the particle itself, only the state.

🔶 Decoy State Protocols

- Real-world lasers emit **weak coherent pulses**, not single photons.
- Eve could exploit multi-photon pulses (photon number splitting attack).
- Send **decoy pulses** (varying intensity) to detect such attacks.

🔷 4. Real-World Quantum Networks

- **Micius satellite (China):** First satellite QKD
- **DARPA & EU QKD testbeds**
- **Fiber-optic and free-space QKD links**

✅ Summary

Quantum communication uses principles like **entanglement, no-cloning, and superposition** to enable secure transmission. BB84 and E91 are foundational protocols for **quantum key distribution (QKD)**.

Day 12

Thursday, July 31, 2025
11:53 AM

📅 Day 12: Quantum Key Distribution – BB84, E91, and Practical Security

🎯 Goal:

Dive deeper into how BB84 and E91 work in practice, including challenges and countermeasures.

🔷 1. BB84 in Depth

Steps:

1. Alice chooses random bits and random basis (Z or X)
2. Sends encoded photons to Bob
3. Bob randomly chooses a measurement basis
4. After transmission, they **compare bases** publicly
5. Discard mismatched ones
6. Analyze error rate from a subset → **detect eavesdropping**

✅ If QBER (Quantum Bit Error Rate) < 11%, key is considered secure

🔷 2. E91 in Depth

- Uses **entangled photons**
- Alice and Bob perform measurements on their photons in chosen bases
- Use **Bell test** to verify that no eavesdropper has tampered
- Doesn't need to trust internal workings of devices (ideal for **device-independent QKD**)

🔷 3. Practical Issues & Attacks

Issue	Description
Photon loss	In fiber or free space
Detector dark counts	False clicks from noise
Side-channel attacks	Exploit imperfections (e.g., detector blinding)
Synchronization errors	Especially in time-bin encoding

🔷 4. Countermeasures

- **Decoy state protocols**: Prevent PNS (Photon Number Splitting)
- **MDI-QKD**: Measurement-device-independent QKD eliminates need to trust detectors
- **Device-Independent QKD**: Based on E91 and Bell inequality violation

---

🔷 5. Security Proofs

- **Shor–Preskill proof**: Proves BB84 is unconditionally secure under ideal assumptions
- Key rate can be calculated based on **QBER** and **photon statistics**

✅ Summary

QKD using BB84 and E91 is **provably secure** under quantum mechanics. While practical systems face engineering challenges, protocols like **MDI-QKD** and **decoy-state QKD** help mitigate real-world risks.

Day 13

Thursday, July 31, 2025

11:57 AM

📘 Day 13: Quantum Teleportation and Photonic Implementations

🎯 Learning Objectives:

By the end of this session, you will:

- Understand the principles of quantum teleportation
- Learn how entanglement enables teleportation
- Explore photonic teleportation experiments and their setup
- See real-world applications of teleportation in quantum networks

🔷 1. What is Quantum Teleportation? – *30 mins*

> Quantum teleportation = Transferring the **quantum state** of a particle from one location to another, using **entanglement** + **classical communication**

- It **does not transfer the particle itself**
- No faster-than-light communication (classical channel still needed)
- Relies on **no-cloning theorem**: you can't copy an unknown quantum state, but you can transfer it

🔷 2. Teleportation Protocol (3-Particle Setup) – *45 mins*

Let's say:

- **Alice** has qubit $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ (unknown state)
- **Alice & Bob** share an entangled pair:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Steps:

1. **Alice performs Bell-state measurement** on her unknown qubit and her half of the entangled pair
2. This measurement collapses Bob's qubit into a state related to $|\psi\rangle$
3. Alice sends **2 classical bits** to Bob (the result of her measurement)
4. **Bob applies a correction** (Pauli gate) based on those bits
5. Now, Bob's qubit is **exactly in state $|\psi\rangle$**

✅ The **original qubit is destroyed**, and its quantum information appears at Bob's side

🔷 3. Teleportation with Photons – *1 hour*

Photonic implementation:

- Use **SPDC** to generate entangled photon pairs
- Encode $|\psi\rangle$ in polarization or time-bin of a single photon
- Alice performs **Bell-state measurement** using beam splitters and detectors
- Classical signal is sent to Bob to **apply unitary correction**

Key components:

- **Polarizing Beam Splitters (PBS)**
- **Wave plates (HWP, QWP)**
- **Single-photon detectors**
- **Fast classical control lines**

🔷 4. Real-World Teleportation Experiments – *45 mins*

Landmark Experiments:

- **1997 Zeilinger Group**: First teleportation of polarization state of a photon
- **2012 China**: Teleportation over 100 km fiber link
- **2017 Micius Satellite**: Teleportation from ground to satellite (1430 km)

✅ These confirm **feasibility of quantum networks** based on teleportation

🔷 5. Applications of Teleportation – *30 mins*

Application	Description
Quantum repeaters	Use teleportation to bridge long distances in QKD
Quantum networks	Build distributed entanglement between nodes
Blind quantum computing	Client sends encrypted quantum data to a server
Quantum error correction	Teleportation used in stabilizer code operations

🔷 6. Limitations and Challenges – *30 mins*

- Bell measurement success is **50% for linear optics** (imperfect with passive optics)
- Requires **high fidelity entanglement**
- Classical channel creates **latency**
- Needs **time synchronization** between nodes

✅ Ongoing research uses **nonlinear optics**, **ancilla photons**, and **feedforward circuits** to improve success rates.

✅ Summary

- Quantum teleportation transfers **information, not particles**
- Requires: **entanglement, Bell measurement, and 2 classical bits**
- Photonic systems are ideal platforms due to ease of state preparation and manipulation
- Crucial for **quantum internet, distributed quantum computing, and secure quantum networks**

Day 14

Thursday, July 31, 2025

12:00 PM

📅 Day 14: Bell-State Measurement and Entanglement Swapping

🎯 Goal:

Understand how to perform Bell-state measurements and how to use them for entanglement swapping — a critical technique for quantum networks and repeaters.

🔷 1. Bell States (Maximally Entangled Two-Qubit States):

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

These are the **Bell basis** and form an orthonormal basis for two qubits.

🔷 2. Bell-State Measurement (BSM)

A **Bell-State Measurement** is a joint quantum measurement that projects two qubits onto one of the four Bell states.

🧪 Photonic Implementation:

- Use **50:50 beam splitter** for interference
- Combine with **polarizing beam splitters (PBS)** and **single-photon detectors**
- Can **only distinguish 2 of 4** Bell states using linear optics:
  - Usually, Ψ^+ and Ψ^- are distinguishable
  - Φ^+ and Φ^- are indistinguishable without extra resources

✅ This limits the **success rate of teleportation to 50%** with standard linear optics

🔷 3. Entanglement Swapping

A fascinating process where **entanglement is generated between particles that never interacted.**

Setup:

- Two entangled pairs:
    - Pair 1: A—B
    - Pair 2: C—D
- Perform BSM on **B and C**
- Result: **A and D become entangled**

✅ This is the **key mechanism for quantum repeaters**, extending quantum communication over long distances.

🔷 4. Real-World Applications

Use Case	Description
Quantum Repeaters	Use entanglement swapping to bridge long distances in QKD
Quantum Internet	Connect multiple nodes using entanglement
Teleportation Networks	Enable chained teleportation between distant users

🔷 5. Limitations and Advancements

Challenge	Solution
Cannot distinguish all 4 Bell states	Use ancillary photons or nonlinear optics
Success rate limited to 50%	Use feedforward circuits, entanglement distillation

✅ Ongoing research explores **time-bin encoded photons**, **frequency multiplexing**, and **nonlinear interactions** to boost BSM fidelity and success.

✅ Summary

- **Bell-state measurements** are essential for quantum teleportation and entanglement swapping.
- **Entanglement swapping** creates new entangled links between distant particles — enabling **scalable quantum networks**.
- Practical BSM in optics is limited but improving with technology like **photon-number-resolving detectors** and **active switching**.

Day 15

Thursday, July 31, 2025
12:34 PM

📅 Day 15: Simple Photonic Quantum Circuits

🎯 Objectives:

- Understand how to build simple quantum circuits using linear optical elements.
- Learn how quantum gates are implemented with beam splitters and phase shifters.
- Explore examples of photonic quantum circuits.

🔁 Recap

In **Day 14**, we discussed **Mach-Zehnder Interferometers (MZIs)** and how they manipulate photon paths using interference. Today we extend those principles to build small **quantum circuits** with real operations on photonic qubits.

🧠 1. What is a Photonic Quantum Circuit?

A **quantum photonic circuit** is a network of optical elements (like beam splitters, phase shifters, and mirrors) designed to manipulate the quantum states of photons (qubits).

Unlike electronic quantum circuits (e.g., superconducting qubits), **photonic circuits** are:

- Passive (require no cooling),
- Based on interference and superposition,
- Built on integrated optics or free-space optics.

🛠️ 2. Building Blocks of Photonic Circuits

Component	Symbol	Function
Beam Splitter (BS)	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i \\ i & 1\end{bmatrix}$	Creates superposition and interference
Phase Shifter (PS)	$\begin{bmatrix}1 & 0 \\ 0 & e^{i\phi}\end{bmatrix}$	Adds a phase shift to the photon
Mirror	—	Redirects photon path
Polarization Rotator	—	Changes the polarization basis (

3. Representing Qubits

Photonic qubits can be represented using **modes** (path encoding) or **polarization**:

- **Path-encoded**:

$$|0\rangle = \text{Photon in path A}, \quad |1\rangle = \text{Photon in path B}$$

- **Polarization-encoded**:

$$|0\rangle = |H\rangle, \quad |1\rangle = |V\rangle$$

4. Circuit Example: Hadamard Gate

The **Hadamard gate** creates a superposition:

Using a 50:50 Beam Splitter:

If a single photon enters one input port of a beam splitter, the output is:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|A\rangle + i|B\rangle)$$

This is equivalent to a Hadamard transformation (up to a global phase).

5. Circuit Example: Mach-Zehnder as a Quantum Gate

The **Mach-Zehnder Interferometer (MZI)** acts like a universal gate:

```scss
Input ──┬── BS ── PS(φ) ── BS ──┬── Output 1
        |                       |
        └───────────────────────┘── Output 2
```

- The interference pattern at the outputs depends on ϕ.
- Can be configured to act as a NOT gate or phase gate.

6. Two-Qubit Operations

Photonic systems are **non-interacting**, so two-qubit gates are harder to implement. Methods include:

- **Post-selection:** Only keep certain measurement outcomes.
- **Non-linear optics:** Use materials where one photon's presence affects another.
- **Measurement-induced entanglement:** Projecting two photons into entangled states via clever circuits.

📝 7. Sample Quantum Circuit

Circuit:

1. Single-photon source.
2. Beam splitter (BS1): creates superposition.
3. Phase shifter (PS).
4. Beam splitter (BS2): interference.
5. Detector D1 and D2.

Output:

- If the PS is adjusted properly, photons will go only to D1 or D2 due to constructive or destructive interference.

🔍 8. Software Tools for Simulation

- **Strawberry Fields (Xanadu)** – Python-based photonic quantum simulator.
- **QuTiP** – Quantum toolbox in Python.
- **PennyLane** – Works with photonic backends.
- **PhotonFlow** – A simulator for quantum optical circuits.

📚 Summary

- Simple quantum circuits with photons use beam splitters and phase shifters.
- Mach-Zehnder interferometers are the foundation of many photonic gates.
- Two-photon gates require non-linear or probabilistic approaches.
- Simulation tools help prototype these circuits.

Day 16

Thursday, July 31, 2025
12:02 PM

📅 Day 16: Quantum Memories for Photonic Systems

🎯 Goal:

Understand what quantum memories are, why they are critical for quantum networks, and how photons can interface with them.

🔷 1. What is a Quantum Memory?

A **quantum memory** stores the quantum state of a qubit (e.g. a photon) **without measuring it**, allowing delayed retrieval.

🧠 Think of it as RAM for quantum computers and networks.

🔷 2. Why Do We Need Quantum Memories?

Use Case	Role of Quantum Memory
Quantum Repeaters	Temporarily store entangled states while waiting for successful links
Synchronization	Ensure photons arrive simultaneously at intermediate nodes
Quantum Networks	Enable communication between nodes asynchronously
Quantum Computing	Store intermediate results in quantum algorithms

🔷 3. Requirements of a Good Quantum Memory

- **High fidelity** (preserve state accurately)
- **Long coherence time** (store for milliseconds–seconds)
- **High efficiency** (store and retrieve with low loss)
- **Wavelength compatibility** (match telecom wavelengths for fiber)
- **Scalability** (integrate with photonic chips)

🔷 4. Types of Quantum Memories

🔶 a. Atomic Ensembles

- Cold atoms in magneto-optical traps or vapor cells
- Interaction via **Electromagnetically Induced Transparency (EIT)**
- Delay and store incoming photon as a collective spin excitation

🔶 b. Rare-Earth-Doped Crystals

- Solid-state: e.g., Pr:YSiO or Eu:YSO
- Use **atomic frequency combs (AFC)** for storage
- Long storage times (seconds) and integratable

🔶 c. Single Ions and Atoms

- Trap one ion/atom in a cavity or trap
- Very high fidelity, but low scalability

🔶 d. Optomechanical Cavities / Superconducting Circuits

- Interface light with mechanical modes or microwave resonators
- Used for transduction (photons ↔ other quantum systems)

🔷 5. How Photons Interact with Memories

- Photon enters medium (e.g., atomic ensemble)
- Laser control field switches the memory to "write" mode
- Photon state mapped onto atomic coherence
- Later, a read-out laser triggers photon emission
- State is retrieved and sent onward

🔷 6. Experimental Advances

- Quantum memories with **90% retrieval efficiency**
- Coherence times > 1 second demonstrated in cryogenic rare-earth crystals
- Hybrid approaches: memory + integrated waveguides

✅ Summary

Quantum memories are vital for **scalable quantum communication**. They act as **buffers and synchronizers** in photon-based networks, bridging the gap between **speed of photons** and **network latencies.**

They are still an active area of research, but strong candidates like **rare-earth crystals** and **cold atomic vapors** are making real-world deployment possible.

Day 17

Thursday, July 31, 2025
12:04 PM

📅 Day 17: Photonic Quantum Error Correction and Fault Tolerance

🎯 Goal:

Learn how quantum information encoded in photons can be protected from errors like loss, noise, and decoherence using **quantum error correction (QEC)** techniques.

🔷 1. Why Error Correction in Quantum Systems?

Unlike classical bits (0 or 1), qubits are fragile:

- **Photon loss** in optical fibers or beam splitters
- **Phase noise** or decoherence over time
- **No-cloning theorem** prevents direct copying for backup

✅ **Quantum error correction (QEC)** encodes logical qubits into multiple physical qubits to **detect and correct** errors without measuring the state directly.

🔷 2. Key Concepts in Quantum Error Correction

Term	Description
Physical qubit	Actual photon or physical system carrying the quantum state
Logical qubit	Protected version of a qubit encoded into several physical qubits
Syndrome measurement	Process of detecting which error occurred without collapsing the quantum state
Fault-tolerance	Ability to operate even when some components fail or are noisy

🔷 3. Photonic Errors and Correction Types

Error Type	Correction Technique
Photon loss	Use **bosonic codes** or **redundant encodings**
Bit/Phase flip	Stabilizer codes like **Shor**, **Steane**, **Surface code**
Mode mismatch	Use **interferometric calibration** and filtering
Decoherence	Time-bin encoding and **active phase stabilization**

🔷 4. Common Photonic Quantum Error Correction Codes

🔶 a. Dual-Rail Encoding

- Logical |0⟩ = |1⟩ in mode A, |0⟩ in mode B
- Logical |1⟩ = |0⟩ in mode A, |1⟩ in mode B
- Simple but vulnerable to **loss**

🔶 b. Bosonic Codes

- Encode qubits in **continuous-variable (CV)** states (e.g., squeezed light)
- Examples: **Gottesman-Kitaev-Preskill (GKP)** code, **cat codes**
- Protects against loss and small displacements

🔶 c. Parity Codes / Cluster-State Codes

- Create **multi-photon entangled states**
- Use **stabilizer measurements** to detect errors
- Implemented in **linear optical quantum computing (LOQC)**

🔷 5. Fault-Tolerant Operations with Photons

- **Teleportation-based gates**: Use entangled photons to apply gates with error detection built-in
- **Fusion gates**: Combine smaller entangled states into larger ones (KLM model)
- **Active feedback**: Real-time feed-forward to correct photon paths or gates

🔷 6. Challenges and Current Research

Challenge	Research Direction
Loss detection	Heralded qubit sources, photon-number resolving detectors
Efficient multi-photon generation	Time multiplexing, integrated sources
Real-time syndrome extraction	Fast photonic switches and logic circuits
Scaling to many qubits	Modular photonic architectures, cluster-state computing

✅ Summary

Quantum error correction is the **cornerstone of reliable quantum computing**. For photonic systems, error correction must handle **loss, decoherence, and gate errors**.

Innovative encodings like **GKP, cat codes, and cluster states** are enabling **fault-tolerant architectures** that may one day scale to millions of qubits.

Day 18

Thursday, July 31, 2025
12:06 PM

📅 Day 18: Continuous-Variable (CV) Quantum Photonics

🎯 Goal:

Understand how **continuous variables** (CV) like position and momentum — rather than discrete qubit states — can be used for **quantum computing and communication** with light.

🔷 1. What is Continuous-Variable Quantum Information?

In most quantum systems, we use **discrete variables**:
Qubits → $|0\rangle$, $|1\rangle$

In **CV systems**, we encode information in **continuous parameters** like:

- **Quadratures** of the electromagnetic field:
  - $\hat{x}$ (position-like)
  - $\hat{p}$ (momentum-like)

These are **observable in light** using techniques like **homodyne detection**.

🔷 2. Why Use Continuous Variables?

Advantage	Explanation
Deterministic operations	No need for probabilistic gates (unlike linear optical QC)
Easy state preparation	Use lasers and optical parametric oscillators (OPOs)
Efficient detection	Homodyne/heterodyne > single-photon detectors
Natural for Gaussian states	Many quantum optical states are Gaussian (e.g., coherent, squeezed)

🔷 3. CV States of Light

State	Description
Coherent state (	\alpha\rangle)
Squeezed state	Reduced uncertainty in one quadrature at cost of other; useful for QKD and metrology
Thermal state	Randomized phase and amplitude; represents noise
Vacuum state	Lowest energy state with zero photons

🔷 4. CV Quantum Gates

In CV systems, operations are defined as **transformations of the quadratures:**

Gate	Transformation
Displacement $\hat{D}(\alpha)$	Shifts $\hat{x}, \hat{p}$ (adds energy)
Squeezing $\hat{S}(r)$	Compresses one quadrature and expands the other
Phase rotation $\hat{R}(\theta)$	Rotates in phase space
Beam splitter	Interferes two modes; entanglement resource
Cubic phase gate (non-Gaussian)	Enables universal quantum computing when combined with Gaussian gates

🔷 5. Measurement in CV Quantum Systems

- **Homodyne detection**: Measures one quadrature (e.g., $\hat{x}$ or $\hat{p}$)
- **Heterodyne detection**: Measures both quadratures approximately
- Enables precise, fast measurements without needing single-photon detectors

🔷 6. Applications of CV Quantum Photonics

Area	CV Technique Used
Quantum Key Distribution (QKD)	Gaussian modulated coherent states (GMCS-QKD)
Quantum computation	CV cluster states + non-Gaussian gates
Quantum sensing	Squeezed light to surpass shot-noise limit
Quantum teleportation	CV entangled states (EPR) enable high-fidelity teleportation

🔷 7. Limitations and Challenges

Limitation	Notes
Non-Gaussian operations hard	Cubic phase gate difficult to implement experimentally
Error correction	Still under development for CV systems (e.g., GKP code)
Sensitivity to noise	Squeezed states are fragile to losses and decoherence

✅ Summary

Continuous-variable quantum photonics provides a **deterministic, scalable, and resource-efficient** alternative to qubit-based quantum computing.

It's especially promising in **quantum communication** and **metrology**, and plays a key role in hybrid quantum systems that combine **discrete and continuous logic**.

Day 19

Thursday, July 31, 2025
12:08 PM

📅 Day 19: Cluster States and Measurement-Based Quantum Computation (MBQC)

🎯 Goal:

Learn how **cluster states** are used as a universal resource for quantum computing — where computation is done by **measuring** rather than applying gates.

🔷 1. What Is Measurement-Based Quantum Computation?

In the **circuit model**, gates are applied in a specific sequence.

In **MBQC**, the computation is:

- Prepared using a **large entangled state** (cluster state)
- Executed by **measuring qubits** (or modes) in specific bases
- Followed by **classical feedforward** to interpret or adjust results

🧠 Idea: Entanglement provides "computational fuel"; measurements guide the computation.

🔷 2. What Is a Cluster State?

A **cluster state** is a highly entangled multipartite quantum state.

For photonics:

- Nodes = photons (or modes)
- Edges = entanglement (via beam splitters or fusion gates)

📍 **Graph Representation:**

Each qubit is a vertex in a graph, and edges represent entangling CZ gates.

Examples:

- 1D cluster = linear computation
- 2D cluster = universal computation

🔷 3. How Cluster States Are Built in Photonic Systems

a. Linear Optical Methods (KLM-type)

- Start with single photons
- Use **fusion gates** (probabilistic) to connect small clusters
- Requires **post-selection** and **heralded detection**

b. Squeezed-Light Based CV Cluster States

- Use **squeezed vacuum states**
- Combine with **beam splitters and phase shifts**
- More scalable using **frequency or time multiplexing**

🔷 4. Quantum Computation via Measurement

Step	Action
Initialize	Create a cluster state (offline)
Measure qubits	In specific basis (X, Y, or rotated)
Feedforward	Use measurement outcomes to adjust future measurements
Result	Output of the computation is obtained from final measurements

🧪 Measurement Choices:

- Determine **which quantum gate** is applied to the logical qubit
- Computation progresses **along the graph**

🔷 5. Universal Computation

MBQC is **universal** if:

- The cluster is **2D (or higher)**
- Measurements can be done adaptively
- Non-Gaussian elements added (in CV model)

In CV MBQC:

- Need **non-Gaussian ancilla** or **nonlinear operations** to be universal

🔷 6. Experimental Progress

Platform	Achievement
Xanadu (Canada)	CV photonic MBQC with time-multiplexed modes
USTC (China)	Multi-photon cluster states
LIGO/QKD labs	CV entanglement for sensing and communication
Squeezed combs	1M-mode cluster states demonstrated

✅ Summary

Cluster states allow quantum computing to be done **purely through measurement**, making them ideal for **photonic systems** where gates are hard to apply.

They're especially powerful in **continuous-variable** platforms using **squeezed light**, and form the backbone of scalable quantum photonic architectures like **Xanadu's Borealis**.

Day 20

Thursday, July 31, 2025
12:11 PM

📅 Day 20: Boson Sampling and Quantum Supremacy with Photons

🎯 Goal:

Understand **Boson Sampling** — a restricted quantum task that photons can perform much faster than classical computers — and its role in demonstrating **quantum supremacy**.

🔷 1. What Is Boson Sampling?

Boson Sampling is a non-universal quantum computation task where:

- **Input**: n single photons
- **Device**: linear optical network (beam splitters + phase shifters)
- **Output**: probability distribution of photons at output ports

✅ Task: Sample from the **output distribution**, which is classically hard to simulate.

🧠 *Why bosons?*
Photons are **bosons** — they exhibit **interference** when multiple paths exist. This interference becomes **exponentially complex** as photon number increases.

🔷 2. Why Is Boson Sampling Important?

- It is **not universal** for quantum computing.
- But it's **much easier to implement** using photons than full gate-based QC.
- Proves a **quantum advantage** for a specific task.

✅ *Sampling from the output distribution of >20 indistinguishable photons is classically intractable.*

🔷 3. Theoretical Foundations

- Output probabilities are proportional to the **permanent** of submatrices of a unitary matrix.
- **Matrix permanents** are #P-hard to compute — even harder than NP-complete problems.
- Simulating large-scale boson sampling is **not feasible** on classical supercomputers.

🔷 4. Experimental Realizations

Institution	Year	Platform	Notes
USTC (China)	2020	**Jiuzhang** photonic circuit	Sampled 50+ photons through 100 modes
Xanadu (Canada)	2022	**Borealis** (time-multiplexed)	216 squeezed modes, 133 spatial channels
Bristol, MIT	2013–2019	Small-scale demos	Validated basic boson sampling behavior

🟢 **Jiuzhang** claimed **quantum supremacy** by achieving in seconds what would take classical computers **billions of years.**

🔷 5. Requirements for Boson Sampling

Component	Role
Single-photon sources	Indistinguishable photon generation (e.g., SPDC, quantum dots)
Interferometer	Optical network (beam splitters + phase shifters)
Detectors	Photon-number-resolving detectors (PNRDs)
Photon indistinguishability	Critical for meaningful interference

🔷 6. Variants of Boson Sampling

Variant	Description
Gaussian Boson Sampling (GBS)	Uses squeezed vacuum instead of single photons
Scattershot Boson Sampling	Uses many SPDC sources with post-selection
Time-bin or Frequency-bin GBS	Enables scalable, multiplexed implementations

🟢 GBS is used in **molecular vibronic spectra simulation**, graph similarity, optimization problems.

🔷 7. Limitations and Criticism

Concern	Response
Not universal	True, but still demonstrates quantum advantage
Sensitive to loss and noise	Experimental systems are improving
Verification is hard	Statistical tests and cross-entropy benchmarking used

✅ Summary

Boson Sampling provides a clear demonstration that **photons** + **linear optics** can perform a task that's classically intractable.

It may not replace universal quantum computing, but it represents a **milestone** in showing that **quantum photonic devices are powerful and practical** for specialized problems.

Day 21

Thursday, July 31, 2025

12:13 PM

📅 Day 21: Quantum Random Number Generation (QRNG) with Photons

🎯 Goal:

Understand how **quantum photonics** enables truly **unpredictable random numbers** and how these are used in **security, cryptography**, and simulations.

🔷 1. Why Random Numbers Matter

Field	Use of Random Numbers
Cryptography	Secure keys, one-time pads
Simulations	Monte Carlo, AI training
Secure communications	Encryption, authentication
Games & lotteries	Fairness & unpredictability

But most classical RNGs are **pseudo-random** (algorithm-based, predictable with seed).

✅ **Quantum RNGs are fundamentally unpredictable** due to quantum indeterminacy.

🔷 2. Principle Behind QRNG

Quantum measurements give **intrinsically random** outcomes.

✅ **Example:**

- Send a single photon through a **50:50 beam splitter**
- Measure which output port it exits:
  - Output A = 0
  - Output B = 1
- Outcome is **random**, guaranteed by quantum mechanics.

🔷 3. Implementations of Photonic QRNGs

🔶 a. Beam Splitter Method

- Simplest setup: single photon, 50:50 beam splitter, two detectors
- Output: 0 or 1 with 50% chance each
- Speed limited by photon source/detector response

🔶 b. Phase Noise-Based QRNG

- Use a laser with **quantum phase noise**
- Measure via **interferometry** → convert analog signal to digital bits
- Very **high speed** (Gbps-scale)

🔶 c. Vacuum Fluctuation Detection

- Detect noise from empty input port (quantum vacuum)
- Requires balanced homodyne detector

🔶 d. Time-of-Arrival Method

- Measure **arrival time** of a photon within a window
- Output many bits depending on resolution

🔷 4. Security Levels

Type	Description
Trusted-device QRNG	Assumes manufacturer is honest
Self-testing QRNG	Uses Bell inequalities to certify randomness
Device-independent QRNG	Fully secure even if device is untrusted (needs entanglement + violation of Bell inequality)

🔷 5. Real-World QRNG Products

Company	Product
ID Quantique	Quantis QRNG (chip + USB)
Quintessence Labs	QRNG based on vacuum noise
Toshiba, IBM	QRNG for data centers
KETS Quantum	Integrated photonic QRNGs

🔷 6. Statistical Testing of QRNGs

Generated bits must pass:

- **NIST test suite**
- **Diehard tests**
- **ENT tests**
  To ensure **uniformity, independence, and entropy**.

✅ QRNGs outperform pseudo-RNGs in passing randomness tests.

🔷 7. Applications of QRNG

Application	Role of QRNG
QKD (Quantum Key Distribution)	Generates random basis and bits
Secure mobile chips	QRNG on chip (for encryption)
Cloud security	Unbiased randomness for keys
Blockchain/Web3	Prevent gaming of lotteries

✅ Summary

Quantum random number generators offer a simple, practical, and **commercially deployable** application of quantum photonics.

They take advantage of **true quantum indeterminacy** to provide secure and verifiable randomness — essential for modern cryptography and secure systems.

Day 22

Thursday, July 31, 2025

12:15 PM

📅 Day 22: Quantum Metrology and Photonic Sensing

🎯 Goal:

Learn how quantum properties of light (like entanglement and squeezing) are used to perform **ultra-precise measurements** beyond classical limits.

🔷 1. What Is Quantum Metrology?

Quantum metrology uses **quantum states of light** to measure physical quantities (time, distance, phase, etc.) **more precisely** than classical techniques.

Classical Limit	Quantum Limit
Shot-noise limit	$\Delta\phi \sim 1/\sqrt{N}$
Heisenberg limit	$\Delta\phi \sim 1/N$

Where N = number of photons used in the measurement.

🔷 2. Quantum States Used in Metrology

State Type	Advantage in Sensing
Coherent state	Classical benchmark (e.g., laser)
Squeezed state	Reduces noise in one quadrature → better sensitivity
Entangled states	Enable precision scaling $1/N$
NOON states	Maximal entangled states: ((

🔷 3. Interferometers in Quantum Sensing

🔶 Mach–Zehnder Interferometer (MZI)

- Input light splits and recombines after one arm acquires a **phase shift.**
- Detect **interference pattern** to measure phase.

Quantum-enhanced versions:

- Inject **squeezed light** in one input → beat shot-noise limit
- Use **entangled photon pairs** to increase phase sensitivity

🔷 4. Applications of Quantum Photonic Sensing

Field	Use Case
Gravitational waves	LIGO uses squeezed light to detect small spacetime ripples
Time standards	Atomic clocks enhanced by quantum correlations
Magnetometry	Detect minute magnetic fields (using nitrogen-vacancy centers, also optically read)
Biophotonics	Low-intensity imaging using entangled photons
Lidar/Optical radar	Quantum illumination for object detection in noisy environments

🔷 5. Quantum Illumination

- Use **entangled photon pairs**
- Send one photon (signal) to target; keep the other (idler)
- Even if entanglement breaks due to noise, **correlation remains**
- Allows better target detection in **lossy, noisy environments**

🛡️ Used for **stealth radar**, underwater detection, and foggy optical imaging.

🔷 6. Quantum-Enhanced Imaging

- Use **ghost imaging**: Image is reconstructed using correlations between entangled photons
- High resolution even with **low light** — great for **biological samples** or **delicate materials**

🔷 7. Limitations and Challenges

Challenge	Notes
Generating high-quality squeezed light	Typically requires nonlinear crystals + stability
Photon loss destroys entanglement	Careful calibration and error correction needed
Scaling up quantum sensors	Integration with photonic chips under development

✅ Summary

Quantum metrology and photonic sensing push the limits of precision in science and engineering. By using **squeezed, entangled, and non-classical light**, we can measure phase, distance, and time with **unprecedented accuracy**.

These technologies are already deployed in **gravitational wave detectors**, **medical imaging**, and **quantum-enhanced radar**.

Day 23

Thursday, July 31, 2025

12:17 PM

📅 Day 23: Time-Bin and Frequency-Bin Encoding in Quantum Networks

🎯 Goal:

Understand how **time-bin** and **frequency-bin** encoding of photons allow robust, high-speed transmission of quantum information — especially in **fiber-based** and **multiplexed** quantum networks.

🔷 1. Why Encode Information in Time or Frequency?

Photons have many degrees of freedom (DoF):

- **Polarization**
- **Path**
- **Time**
- **Frequency**
- **Orbital Angular Momentum (OAM)**

✅ **Time-bin** and **frequency-bin** encodings are:

- Stable in **optical fibers**
- Compatible with **telecom infrastructure**
- Ideal for **multiplexing and scaling**

🔷 2. Time-Bin Encoding

🕒 What is it?

Quantum information is stored in **early** and **late** arrival times of a photon.

Logical State	Representation
	0⟩
	1⟩
Superposition	Photon in both bins (coherent pulse train)

✅ Acts like a **temporal qubit**

⚙️ How It's Implemented:

- Use **unbalanced interferometers** (e.g., Franson or Mach–Zehnder)
- Delay one path by nanoseconds
- Create **superposition of time states**

📌 Applications:

- **Quantum Key Distribution (QKD)**
- **Entanglement distribution** over long fibers
- Compatible with **quantum memories** (atomic or rare-earth-based)

🔷 3. Frequency-Bin Encoding

What is it?

Use different **frequency channels** (bins) to encode quantum states.

Logical State	Representation
	0⟩
	1⟩
Superposition	Coherent superposition of f_0 and f_1

✅ Especially suitable for **dense wavelength division multiplexing (DWDM)**

⚙️ How It's Implemented:

- Use **frequency combs**, **electro-optic modulators (EOMs)**, or **Fourier-transform pulse shapers**
- Measure with **dispersive optics**, spectrometers, or **etalon filters**

📌 Applications:

- **High-throughput quantum communication**
- Multiplexed **boson sampling** (Xanadu's Borealis)
- **Quantum frequency conversion** (interface with quantum memories)

🔷 4. Comparison: Time-Bin vs Frequency-Bin

Feature	Time-Bin Encoding	Frequency-Bin Encoding
Fiber Stability	High	High
Multiplexing	Moderate (temporal limits)	Excellent (DWDM standards)
Detector Bandwidth Need	Low	High
Interference Control	Needs delay interferometers	Needs frequency control
Clock Synchronization	Critical	Less critical

🔷 5. Real-World Implementations

Platform	Use of Time/Frequency Bins
Micius Satellite (China)	Time-bin entanglement over 1,200 km
Xanadu (Canada)	GBS using frequency-encoded squeezed states
Toshiba & IDQ	Time-bin QKD in telecom fibers
Quantum repeaters	Time-bin encoded photons + atomic memories

🔷 6. Challenges

Challenge	Notes
Interferometer stability (time-bin)	Needs temperature-controlled enclosures
Spectral resolution (frequency-bin)	High-precision modulators and filters required
Mode matching	Important in multiplexed photonic circuits

✅ Summary

Time-bin and frequency-bin encoding are powerful tools for **robust, scalable, and high-speed** quantum communication.

They offer excellent compatibility with **telecom-grade infrastructure**, and are essential for **multi-user quantum networks**, **quantum memories**, and **photonic quantum computing**.

Day 24

Thursday, July 31, 2025
12:19 PM

📅 Day 24: Quantum State Tomography and Process Tomography with Photons

🎯 Goal:

Learn how to **experimentally reconstruct the quantum state** (or the quantum process) using **measurements on photons**. This is essential for testing, verifying, and debugging quantum devices.

🔷 1. What Is Quantum Tomography?

🔍 **Tomography** = Reconstructing an **unknown object** (in this case, a quantum state or operation) using **many measurements**.

There are two main types:

Type	Purpose
State Tomography	Reconstruct the density matrix of a quantum state
Process Tomography	Characterize the full behavior of a quantum operation (gate or channel)

🔷 2. Quantum State Tomography (QST)

🧠 Goal:

Given an **unknown quantum state** (e.g., a single photon qubit), determine its **density matrix** ρ.

🛠 How It Works:

1. **Prepare many copies** of the same state
2. **Measure** in different bases (X, Y, Z)
3. **Collect statistics** from each basis
4. **Reconstruct** ρ using inversion or optimization

✅ **Example: Single Qubit (Photon)**

- Measure polarization in:
  - **Z basis**: |H⟩ / |V⟩
  - **X basis**: |+⟩ / |–⟩
  - **Y basis**: |R⟩ / |L⟩

With the expectation values ⟨X⟩, ⟨Y⟩, ⟨Z⟩, reconstruct:

$$\rho = \frac{1}{2}\left(I + \langle X\rangle\sigma_x + \langle Y\rangle\sigma_y + \langle Z\rangle\sigma_z\right)$$

✅ *Works for multi-qubit states too, but scales exponentially!*

🔷 3. Quantum Process Tomography (QPT)

🧠 **Goal:**

Characterize an **unknown quantum operation** $\mathcal{E}(\rho)$

🛠 **Steps:**

1. Prepare **known input states** (|0⟩, |1⟩, |+⟩, |R⟩)
2. Apply the **quantum process** (e.g., gate or channel)
3. Perform **state tomography** on the outputs
4. Fit results to a **process matrix** (χ matrix) that describes $\mathcal{E}$

✅ Useful for verifying **photonic gates**, **entangling circuits**, and **optical channels**

🔷 4. Tools for Tomography in Photonics

Component	Function
Polarization rotators (waveplates)	Set measurement basis
Beam splitters + interferometers	Enable superposition basis measurements
Photon detectors	Count outcomes in each basis
Statistical software	Fit measurement data to estimate ρ or χ

🔷 5. Advanced Tomography Techniques

Technique	Feature
Maximum likelihood estimation (MLE)	Ensures valid physical state (positive, trace 1)
Bayesian tomography	Provides uncertainty/confidence bounds
Compressed sensing	Reduces number of measurements for sparse states
Direct measurement	Avoids full tomography by estimating observables of interest

🔷 6. Limitations and Challenges

Challenge	Notes
Scales exponentially with qubit count	Requires ~3^n measurements
Photon losses & detector errors	Must be corrected/calibrated
State preparation errors	Can affect process fidelity
Real-time tomography	Still difficult at scale; requires fast electronics

✅ Summary

Quantum tomography is a **foundational tool** for analyzing and validating **quantum photonic systems**.

It allows us to **reconstruct quantum states**, verify **gate operations**, and detect **imperfections** in experiments — playing a key role in **quantum control, benchmarking, and error correction**.

Day 25

Thursday, July 31, 2025

12:21 PM

📅 Day 25: Photonic Quantum Machine Learning (QML)

🎯 Goal:

Understand how **photonic quantum systems** can be used to perform machine learning tasks — either as **quantum processors** or **data encoders.**

🔷 1. Why Combine Quantum and Machine Learning?

Classical ML Limitation	Quantum Advantage
High-dimensional data	Hilbert space scales exponentially
Long training times	Quantum parallelism
Feature extraction	Quantum embeddings can be richer
Optimization problems	Quantum sampling or variational circuits

✅ Using **photons** brings **scalability, low noise, and high speed** — especially in **optical neural networks** and **Gaussian Boson Sampling**.

🔷 2. Role of Photonics in QML

Photons can serve as:

- **Data carriers** (encoded in polarization, time-bin, frequency-bin, etc.)
- **Quantum processors** for variational circuits
- **Sampling engines** for probabilistic models
- **Hybrid tools** in classical-quantum ML workflows

🔷 3. Encoding Classical Data into Photons

You need to load data into quantum states — this is called **quantum feature mapping**.

Methods:

Encoding Type	Example
Amplitude encoding	Use amplitudes of photon modes (requires normalization)
Qubit encoding	Encode data into polarization, time-bin, or path
CV encoding	Use squeezed states or displacements of Gaussian modes
Kernel embedding	Data mapped to quantum Hilbert space → used for SVMs or clustering

🔷 4. Quantum Circuits for Learning (Photonic Platforms)

a. Variational Quantum Circuits (VQCs)

- Parameterized optical networks (beam splitters, phase shifters)
- Trained to minimize loss functions

b. CV Quantum Neural Networks

- Gaussian operations + non-Gaussian gates (like Kerr or cubic phase)
- Implemented with squeezed light and homodyne detection

c. Quantum Kernels

- Use quantum states as **feature space**
- Apply **kernel methods** (like SVMs) on quantum similarity measures

🔷 5. Gaussian Boson Sampling for ML

Gaussian Boson Sampling (GBS) can be used for:

ML Task	How GBS Helps
Graph similarity	GBS maps graphs to photon distributions
Clustering	Sample clusters from probabilistic model
Molecule classification	Encode vibronic spectra into photonic samples

🏛 Xanadu's **PennyLane** + **Strawberry Fields** libraries let you experiment with this.

🔷 6. Hybrid Quantum-Classical ML

A common architecture:

1. Classical preprocessing (e.g., feature selection)
2. Encode into photonic quantum circuit
3. Perform quantum transformation or sampling
4. Classically optimize parameters (using gradient descent)

🧠 Especially powerful in **noisy intermediate-scale quantum (NISQ)** settings.

🔷 7. Tools and Libraries

Tool	Use Case
Strawberry Fields (Xanadu)	CV quantum photonic simulation
PennyLane	Hybrid quantum-classical ML
TensorFlow Quantum	Integrate quantum circuits with ML models
Qiskit Machine Learning	Support for IBM platforms (less photonic-specific)

🔷 8. Experimental Outlook

Platform	Progress
Xanadu Borealis	CV GBS, VQCs, real photonic chips
MIT Photonic Bands	Optical neural networks
ORCA Computing	Memory-integrated photonic ML
Lightmatter, Lightelligence	Analog optical ML accelerators (non-quantum, but related)

✅ Summary

Quantum machine learning with photons combines the **best of both worlds** — quantum speedups and ML's data handling power.

Photonic platforms (especially **continuous-variable systems**) are **scalable, fast, and already usable** for tasks like **clustering, classification, graph similarity**, and more.

Day 26

Thursday, July 31, 2025
12:23 PM

📅 Day 26: Quantum Repeaters and Photonic Quantum Networks

🎯 Goal:

Understand how **quantum repeaters** enable long-distance quantum communication using **photonic entanglement** and how this forms the foundation for **quantum networks**.

🔷 1. The Problem with Long-Distance Quantum Communication

Unlike classical signals, **quantum information can't be amplified** due to the **no-cloning theorem**.

Challenge	Cause
Photon loss	Fiber absorption & scattering
Decoherence	Timing jitter, polarization drift
No-cloning rule	Prevents copying qubits mid-way

✅ This limits **direct QKD or teleportation** to ~100–150 km in optical fiber.

🔷 2. What Is a Quantum Repeater?

A **quantum repeater** is a device or protocol that allows **long-distance entanglement distribution** by:

1. Creating **short-range entanglement links**
2. Using **entanglement swapping** to connect them
3. Optionally applying **entanglement purification**

✅ Analogous to classical repeaters, but based on **entanglement and measurement**, not amplification.

🔷 3. Key Components of a Quantum Repeater

Component	Role
Entangled photon sources	SPDC, quantum dots
Quantum memories	Store photons temporarily (e.g., atomic ensembles)
Bell-state measurement (BSM)	For entanglement swapping
Heralded detection	Signal success/failure without disturbing state
Classical communication	Coordinates between nodes

🔷 4. Entanglement Swapping — The Core Idea

Let's say:

- Nodes A–B share entangled photons
- Nodes B–C also share entangled photons

Then:

- Perform a **BSM at node B**
- Result: A and C become **entangled**, even though they never interacted

🧠 This is the **quantum repeater protocol**!

🔷 5. Types of Quantum Repeaters

Type	Features
First-gen (Heralded)	Probabilistic entanglement; needs memory
Second-gen (Purified)	Adds purification for higher fidelity
Third-gen (All-photonic)	No memory; uses photonic cluster states (hard to build, but scalable)

🔬 All-photonic repeaters are being explored using **time-bin encoded cluster states** and **fusion gates**.

🔷 6. Photonic Quantum Networks

A **quantum network** is a set of nodes (quantum processors or users) connected by **quantum channels** (typically photons in fiber or free-space).

Use Case	Functionality
Quantum Key Distribution (QKD)	Secure communication
Distributed quantum computing	Share quantum states across nodes
Quantum clock synchronization	High-precision global timing
Blind quantum computing	Server does computation without knowing data

🔷 7. Real-World Demonstrations

Project/Org	Achievement
Micius satellite (China)	Satellite-to-ground entanglement & QKD over 1200 km
DARPA Quantum Network (USA)	Early QKD field tests
European OpenQKD	Fiber-based quantum network testbeds
QuTech, Xanadu, ORCA	Memory-compatible repeaters and cluster states

🔷 8. Challenges and Ongoing Research

Challenge	Research Focus
Efficient quantum memories	Long coherence, fast read/write
Photon indistinguishability	High-quality sources needed
Bell-state measurement limits	Linear optics only allows 50% success
Scaling repeaters	Integration with telecom infrastructure

✅ Summary

Quantum repeaters and **photonic networks** are key to building the **quantum internet**. Photons serve as the ideal carriers for entanglement over long distances, but maintaining fidelity requires **repeaters, memories, and smart protocols.**

Photonic platforms are already demonstrating **satellite QKD**, **entanglement distribution**, and **long-distance teleportation** — all cornerstones of future **quantum-secure communication**.

Day 27

Thursday, July 31, 2025
12:25 PM

📅 Day 27: Quantum Error Correction in Photonic Systems

🎯 Goal:

Understand how **quantum error correction (QEC)** is implemented in **photon-based systems**, and explore encoding strategies used to combat **loss, noise, and decoherence.**

🔷 1. Why Error Correction Is Needed

Quantum systems — especially photonic ones — are vulnerable to:

- **Photon loss**
- **Detector dark counts**
- **Mode mismatch**
- **Phase drift or misalignment**

🧠 Quantum information **cannot be copied** (no-cloning theorem), so classical error correction **doesn't apply** directly.

✅ QEC uses **entanglement** + **redundancy** + **syndrome measurements** to protect quantum states.

🔷 2. Types of Errors in Photonic Systems

Error Type	Description
Photon loss	Photon disappears during transmission or in circuits
Dephasing	Unwanted phase shift in interferometers
Bit flip / phase flip	Fluctuations due to thermal or optical noise
Mode mismatch	Overlap errors in time/frequency/spatial modes

🔷 3. Photon-Based QEC Strategies

✅ a. Repetition Codes (Loss-Tolerant)

Simple 3-qubit code:

$$|0_L\rangle = |000\rangle, \quad |1_L\rangle = |111\rangle$$

- Can detect and correct **bit-flip errors**
- In photonics: encode **logical qubit** into **multiple photons** across paths or time bins

✅ b. Parity Encoding

- Use parity checks across multiple photons
- Detect missing or flipped photons by measuring certain correlations
- Useful in **linear optics quantum computing (LOQC)**

✅ c. Bosonic Codes

Use **continuous-variable (CV)** modes (like squeezed light or oscillators) to encode qubits.

Code Type	Description
GKP Code	Encodes logical 0 and 1 as grid states in phase space (highly error-resilient)
Cat Code	Superpositions of coherent states (
Binomial Code	Discrete photon number encoding with error-correcting spacing

🔷 4. Cluster-State Error Correction (Measurement-Based QEC)

In **measurement-based quantum computing (MBQC)** using photons:

- Build a **large entangled resource state** (cluster state)
- Perform computation via **adaptive measurements**
- QEC is done by embedding **logical qubits** in **fault-tolerant cluster state topologies** (like surface codes)

🟦 Photonic cluster states are created using **fusion gates** and **probabilistic entanglement**

🔷 5. Experimental Implementations

Organization	Technique
Xanadu	CV encoding with GKP-like states
ORCA Computing	Photonic memory compatible with QEC
QIT@UNSW, Bristol	Linear-optics repetition codes
LIGO + Squeezed Light	Phase noise suppression (not QEC, but error mitigation)

🔷 6. Key Challenges in Photonic QEC

Challenge	Notes
Noisy state preparation	Hard to generate clean resource states
Photon loss	Dominant error in fiber and chips
Limited deterministic gates	Most photonic gates are probabilistic
Scalability	Requires multiplexing and fast feed-forward logic

✅ Summary

Quantum error correction in photonics focuses on tackling **loss and noise** using **redundant encodings, bosonic codes, and cluster states**. Though challenging due to photon loss and non-deterministic gates, **bosonic codes** and **CV platforms** offer promising approaches.

As photonic integration and detector fidelity improve, **QEC will be central** to building **fault-tolerant, scalable photonic quantum computers**.

Day 28

Thursday, July 31, 2025
12:28 PM

📅 Day 28: Quantum Simulation Using Photonic Systems

🎯 Goal:

Understand how photons and optical circuits can be used to simulate **complex quantum systems**, such as **molecules, spin chains**, and **bosonic models**.

🔷 1. What Is Quantum Simulation?

🔬 A **quantum simulator** is a controllable quantum system (here, photonic) used to mimic the behavior of another (often less accessible) quantum system.

Type	Example
Analog simulation	Build system with similar dynamics (e.g., optical lattice = Hubbard model)
Digital simulation	Use universal gates to model time evolution step-by-step

✅ **Photons are especially useful for analog simulations**, particularly for **bosonic systems** and **non-interacting particles.**

🔷 2. Why Use Photons for Simulation?

Advantage	Why Photons Help
Easy to control	Use beam splitters, modulators, interferometers
Low decoherence	Photons don't interact strongly with environment
Suitable for bosonic systems	Natural for vibrational spectra, phonons, etc.
High-speed operations	Optical systems run at light speed
Compatible with chips	Integrated photonics for scaling simulations

🔷 3. Types of Photonic Quantum Simulations

✅ a. Gaussian Boson Sampling (GBS)

- Sample from a **Gaussian photonic state**
- Simulates properties of **vibronic spectra**, **graph similarity**, and **molecular modes**
- Hard to simulate classically = **quantum advantage**

🔗 Implemented using:

- Squeezed light sources
- Linear interferometers
- Photon-number resolving detectors

🧪 **Used by Xanadu** to simulate molecules like **formaldehyde, water, caffeine**!

✅ b. Quantum Walks with Photons

- Simulate particle motion on graphs/lattices using **multi-path interference**
- Types:
  - **Discrete-time** walks (with coin operators)
  - **Continuous-time** walks (waveguide arrays)

🧠 Applications:

- Energy transport in **photosynthesis**
- **Anderson localization**
- Search algorithms

✅ c. Spin Models and Lattice Simulators

- Encode **spin-1/2 systems** using photon polarization or path
- Create **Heisenberg** or **Ising** models via controlled interactions and measurements
- Use photonic cluster states for **1D/2D lattice simulations**

🔷 4. Encoding Simulated Systems into Photonic States

Simulated Quantity	Photonic Encoding
Fermionic modes (via Jordan-Wigner)	Polarization/path
Bosonic modes	Photon-number states
Couplings/energies	Phase shifters, reflectivities
Time evolution	Repeated gate applications or dynamic interferometers

🔷 5. Tools and Platforms

Tool/Platform	Capability
Strawberry Fields	GBS, CV simulation
PennyLane	Hybrid simulation + training
Xanadu Borealis	Large-scale CV photonic simulator
Fermionic simulators	Simulated via photonic encodings using Pauli matrices

🔷 6. Challenges in Photonic Simulation

Challenge	Reason
Photon loss	Reduces simulation fidelity
Limited photon number	Scaling GBS to many modes is hard
Boson distinguishability	Imperfect interference reduces accuracy
Post-selection limits	Many simulations are probabilistic or rely on post-selection

✅ Summary

Photonic quantum simulators are powerful tools to **explore complex quantum systems**, especially those involving **bosons, molecules**, and **non-classical light**.

Technologies like **Gaussian Boson Sampling**, **quantum walks**, and **cluster state simulations** offer real-world platforms for simulating **chemistry, condensed matter physics**, and **quantum dynamics** — with many already being **experimentally realized**.

Day 29

Thursday, July 31, 2025
12:30 PM

📅 Day 29: Photonic Quantum Computing with Cluster States and Measurement-Based Models

🎯 Goal:

Understand how **measurement-based quantum computing (MBQC)** using **photonic cluster states** allows scalable quantum processing.

🔷 1. What Is Measurement-Based Quantum Computing?

- Also called **one-way quantum computing**
- Instead of applying gates sequentially:
  1. **Prepare a large, highly entangled state** (called a **cluster state**)
  2. **Perform single-qubit measurements** in specific bases
  3. The measurement outcomes drive the computation

✅ Once the cluster is built, computation proceeds via **adaptive measurements only** (no additional gates needed).

🔷 2. Why MBQC Is Suited for Photons

Reason	Explanation
Photons don't naturally interact	So gates are hard to apply directly
But measurements are easy	Detectors + beam splitters = fast & reliable
Cluster states can be built probabilistically	Using **fusion gates**, beam splitters, and entangled sources
Supports **time-multiplexing**	Use same hardware over many time slots for scalability

🔷 3. Photonic Cluster States

🧬 What Is a Cluster State?

A highly entangled multi-qubit state, typically arranged in a **graph** (e.g., linear, 2D lattice).

Basic cluster:

$$|C\rangle = \prod_{(i,j)\in E} CZ_{ij} \bigotimes_i |+\rangle_i$$

Where:

- $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
- CZ = Controlled-Z gate entangling connected qubits

🔷 4. Creating Cluster States with Photons

- Use **SPDC sources** to generate entangled photon pairs
- Use **fusion gates (Type-I, Type-II)** to stitch pairs into bigger clusters
- Use **interferometers, phase shifters, and PBS** for routing and interference

✅ **Measurement-only computation** begins after cluster is formed

🔷 5. Time-Multiplexed Cluster States

Instead of generating a large 2D array of physical qubits, use:

- A small number of devices
- Generate photons at different **time bins**
- Route them using **delay lines and optical loops**

✅ Achieves scalability using only a **single chip and few components**

🏭 Used by **Xanadu's Borealis** photonic quantum processor

🔷 6. Computation via Adaptive Measurements

- Measure each qubit in a chosen basis (X, Y, or rotated)
- Later measurement angles depend on earlier outcomes (classical feed-forward)
- Measurement pattern = quantum algorithm

🧠 Requires **fast electronics and classical controller** to update measurement settings in real-time

🔷 7. Error Correction in MBQC

- Use **topological cluster states** (e.g., Raussendorf lattice) for **fault tolerance**
- Embed **surface codes** into photonic cluster state structure
- Loss-tolerant designs use **redundant paths or teleportation chains**

🔷 8. Real-World Implementations

Platform	Achievement
Xanadu	Time-multiplexed cluster states for GBS and computing
University of Tokyo	Large cluster generation with fusion gates
Bristol, UCL	Measurement-based gates using polarization encoding
ORCA Computing	Photonic memory integration with MBQC

✅ Summary

Measurement-based photonic quantum computing turns **entangled light** into a **computational resource** — with logic emerging from **measurements**.

By generating **cluster states**, especially in **time-multiplexed** architectures, photonic platforms are achieving scalable, programmable, and fault-tolerant quantum computing — **without requiring photon-photon interactions.**

Day 30

Thursday, July 31, 2025
12:31 PM

📅 Day 30: Future Directions and Career Opportunities in Quantum Photonics

🎯 Goal:

Summarize emerging trends, challenges, and **real-world applications** of quantum photonics, and provide a **roadmap for careers and research opportunities**.

🛰️ 1. Future Directions in Quantum Photonics

🔷 a. Scalable Photonic Quantum Computers

- **Integrated photonics** on silicon or lithium niobate
- **Time-multiplexed cluster states**
- **Deterministic single-photon sources** (quantum dots, on-chip sources)

▶️ Companies: Xanadu, PsiQuantum, ORCA Computing, Lightmatter

🔷 b. Quantum Internet & Global Quantum Networks

- **Satellite-based QKD** (e.g., Micius satellite)
- **Quantum repeaters** using entangled photons and memories
- Fiber + free-space **hybrid networks**

▶️ Long-term goal: **Global quantum-secure communication**

🔷 c. Photonic Quantum Machine Learning

- **Quantum kernel methods**
- **Quantum-enhanced classifiers**
- Optical neural networks using quantum or classical photonics

▶️ Used in **finance**, **drug discovery**, and **pattern recognition**

🔷 d. Interfacing with Other Quantum Platforms

- Photon-to-spin interfaces (e.g., NV centers, trapped ions)
- Photon-to-superconductor links for hybrid networks
- Quantum memories for buffering photons

▶️ Goal: **Modular quantum computing**

🎓 2. Career Opportunities in Quantum Photonics

🔷 a. Research Pathways

Level	Focus Area
M.Sc / M.Tech	Photonics, Quantum Optics, Nanophotonics
PhD	Integrated photonics, quantum light sources, error correction
Postdoc	Device development, networking, QML, CV quantum computing

✅ Institutions: MIT, Harvard, Oxford, TU Delft, IISc, TIFR, IITs, IQC, CQT Singapore

🔷 b. Industry Roles

Role	Skills Needed
Quantum Photonics Engineer	Optics, integrated photonic design, lab experience
Quantum Algorithm Developer	Quantum computing + Python (Qiskit, PennyLane)
Hardware Research Scientist	Materials, nano-fabrication, quantum optics
Quantum Applications Engineer	ML, simulation, customer solutions for quantum APIs

✅ Companies: Xanadu, PsiQuantum, ORCA Computing, IBM, Rigetti, QuEra, Quandela, ID Quantique, Aliro, AWS Braket

🔷 c. Skills to Build

Domain	What to Learn
Optics & Photonics	Polarization, interferometry, waveguides, nonlinear optics
Quantum Mechanics	Entanglement, measurement theory, qubits, CV systems
Programming	Python, Qiskit, Strawberry Fields, PennyLane
Mathematics	Linear algebra, complex numbers, Fourier optics
Fabrication/Simulation	Lumerical, COMSOL, MATLAB, Meep

🔷 d. How to Stay Updated

- 📚 Journals: *Physical Review A, Nature Photonics, npj Quantum Info*
- 🧠 Conferences: QCrypt, CLEO, APS March, Q2B, IEEE QCE
- 🧑‍🔬 Communities: QWorld, Quantum Open Source Foundation, Photonics Society
- 💻 GitHub: XanaduAI, Qiskit, PennyLane, QuTiP

🏁 Summary and What's Next?

🎓 **You've completed a 30-day course** in **Quantum Photonics** covering:

- Core concepts in quantum optics
- Photon-based qubits and gates
- Quantum communication and QKD
- Error correction, QML, MBQC, and simulation
- Hardware platforms and real-world applications

💡 Next steps:

- Pick a focus: hardware, algorithms, or applications
- Build projects using tools like **Strawberry Fields** or **Qiskit**
- Contribute to open-source or intern with quantum companies/labs
- Apply for research fellowships or job roles aligned with your interests