Quantum Physics and Engineering

Quantum Optics and Photonics

Photon – the elementary quantum of the electromagnetic field, carrying energy $E = \hbar\omega$ and momentum $p = \hbar k$. In quantum optics the photon replaces the classical wave amplitude; its particle-like detection events underlie the statistical description of light. For example, in a weak-coherent laser pulse the average photon number $\langle n \rangle$ may be less than one, yet individual detection events reveal the granularity of the field.

Quantum state – a complete description of a system's physical properties, represented by a state vector $|\psi\rangle$ in Hilbert space or by a density operator ρ. In photonics the state often refers to the mode occupancy, polarization, and phase. A pure state satisfies $\rho = |\psi\rangle\langle\psi|$, while a mixed state reflects classical uncertainty or decoherence.

Fock state – also called a number state, denoted $|n\rangle$, with exactly n photons in a given mode. Fock states are eigenstates of the photon-number operator $\hat{N} = \hat{a}^\dagger\hat{a}$, where $\hat{a}^\dagger$ and $\hat{a}$ are creation and annihilation operators. They are essential for describing nonclassical light, such as in photon-counting experiments, and are generated in practice by heralded spontaneous parametric down-conversion.

Coherent state – the quantum state most closely resembling a classical electromagnetic wave, written $|\alpha\rangle$ where α is a complex amplitude. Coherent states are eigenstates of the annihilation operator $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$ and possess Poissonian photon-number statistics. Lasers operating well above threshold emit light that is well approximated by a coherent state, making this concept a cornerstone for understanding laser noise and phase stability.

Squeezed state – a nonclassical state in which quantum fluctuations of one quadrature are reduced below the vacuum level at the expense of increased fluctuations in the conjugate quadrature, respecting the Heisenberg uncertainty principle. Squeezing is quantified by the squeezing parameter r; the variance of the squeezed quadrature scales as e^{-2r}. Applications include quantum-enhanced interferometry, where squeezed light lowers the shot-noise limit.

Entanglement – a correlation between subsystems that cannot be described by any product of local states. In photonic systems, polarization entanglement is often realized using type-II spontaneous parametric down-conversion, producing Bell states such as $|\Psi^+\rangle = (|HV\rangle + |VH\rangle)/\sqrt{2}$. Entangled photon pairs enable protocols like quantum teleportation and quantum key distribution.

Bell state – one of the four maximally entangled two-qubit states. The four Bell states ($|\Phi^+\rangle$, $|\Phi^-\rangle$, $|\Psi^+\rangle$, $|\Psi^-\rangle$) form an orthonormal basis for the joint Hilbert space of two photons. They are exploited in entanglement swapping, superdense coding, and device-independent quantum cryptography.

Quantum efficiency – the probability that an incident photon produces a detectable signal in a photodetector. High quantum efficiency (often $> 90\,\%$ for superconducting nanowire single-photon detectors) is crucial for low-loss quantum communication and for closing detection loopholes in Bell tests.

Spontaneous emission – the process by which an excited atom or quantum emitter decays to a lower energy level, emitting a photon without external stimulation. The rate is given by the Einstein A coefficient and can be modified by the photonic environment, as described by the Purcell effect.

Stimulated emission – the process in which an incoming photon induces an excited emitter to release a second photon that is coherent with the stimulating photon. This principle underlies laser amplification and optical amplifiers, where the gain medium provides population inversion.

Cavity quantum electrodynamics (cavity QED) – the study of the interaction between quantum emitters and a quantized field confined in a resonator. The strong-coupling regime, where the emitter–field coupling g exceeds both the cavity decay rate κ and the emitter decoherence rate γ, leads to phenomena such as vacuum Rabi splitting and photon blockade.

Jaynes-Cummings model – a fundamental theoretical framework describing a two-level atom interacting with a single mode of the quantized field. The Hamiltonian $\hat{H} = \hbar\omega_c \hat{a}^\dagger\hat{a} + \frac{1}{2}\hbar\omega_a \hat{\sigma}_z + \hbar g (\hat{a} \hat{\sigma}_+ + \hat{a}^\dagger \hat{\sigma}_-)$ predicts Rabi oscillations, collapse-and-revival dynamics, and dressed-state energy ladders.

Nonlinear optics – the branch of optics dealing with light-matter interactions where the induced polarization P depends nonlinearly on the electric field E. The second-order susceptibility $\chi^{(2)}$ enables processes such as second-harmonic generation (SHG) and sum-frequency generation, while the third-order susceptibility $\chi^{(3)}$ underlies four-wave mixing and the Kerr effect.

Second-harmonic generation – a $\chi^{(2)}$ process in which two photons at frequency ω combine to produce a photon at 2ω. Phase-matching techniques (e.G., Birefringent or quasi-phase-matched crystals) are required to conserve momentum, allowing efficient conversion in nonlinear crystals like lithium niobate.

Parametric down-conversion (PDC) – a $\chi^{(2)}$ process where a pump photon at frequency ω_p splits into a pair of lower-frequency photons (signal ω_s and idler ω_i) satisfying energy conservation $\omega_p = \omega_s + \omega_i$. In the spontaneous regime, PDC provides a source of entangled photon pairs; in the stimulated regime, it is used for optical parametric oscillators (OPOs) and amplifiers.

Quantum dot – a semiconductor nanostructure that confines charge carriers in all three dimensions, producing discrete energy levels analogous to an atom. Quantum dots act as on-demand single-photon emitters, with applications in quantum communication and integrated photonic circuits.

Waveguide – a structure that guides electromagnetic waves by confining them in transverse dimensions, typically using total internal reflection. Integrated photonic waveguides on silicon or silicon nitride platforms enable compact manipulation of light, including coupling, splitting, and phase control.

Photonic crystal – a periodic dielectric structure that creates a photonic bandgap, preventing propagation of certain frequencies. Defect cavities within photonic crystals can achieve ultra-high quality factors (Q) and small mode volumes, enhancing light-matter interaction for cavity QED experiments.

Bandgap – the range of frequencies for which propagation is forbidden in a photonic crystal. By engineering the lattice constant and refractive index contrast, one can tailor the bandgap to control spontaneous emission or to create waveguide channels within the crystal.

Dispersion – the dependence of the phase velocity $v_p = \omega/k$ on frequency. Material dispersion arises from frequency-dependent refractive index, while waveguide dispersion results from geometry. Understanding dispersion is essential for designing broadband devices and for managing pulse broadening in fibers.

Group velocity – the velocity at which the envelope of a pulse propagates, given by $v_g = d\omega/dk$. In anomalous dispersion regimes, v_g can exceed c or become negative, leading to superluminal or slow-light effects exploited in optical buffering.

Group velocity dispersion (GVD) – the second derivative of the propagation constant with respect to frequency, quantified by β_2. Positive β_2 leads to pulse broadening (normal dispersion), while negative β_2 compresses pulses (anomalous dispersion). GVD management is critical in ultrafast laser design and soliton propagation.

Optical fiber – a dielectric waveguide that confines light by total internal reflection. Single-mode fibers support only the fundamental LP_{01} mode, allowing low-loss transmission over long distances. Fiber-based nonlinear processes, such as supercontinuum generation, rely on the interplay of dispersion and Kerr nonlinearity.

Mode – a specific field distribution that satisfies the boundary conditions of a waveguide or resonator. In a cavity, longitudinal modes are separated by the free spectral range $\Delta\nu = c/2L$, while transverse modes are characterized by Hermite-Gaussian or Laguerre-Gaussian patterns.

Polarization – the orientation of the electric field vector in a transverse electromagnetic wave. In quantum optics, polarization serves as a convenient qubit basis, with horizontal (H) and vertical (V) states forming the computational basis. Polarization controllers and waveplates manipulate this degree of freedom.

Stokes parameters – a set of four real numbers (S_0, S_1, S_2, S_3) that fully describe the state of polarization. S_0 denotes total intensity, while S_1, S_2, S_3 quantify linear, diagonal, and circular polarization components. They are measured using polarimetric setups and are useful for characterizing partially polarized light.

Density matrix – a representation of a quantum state that can describe both pure and mixed states. For a single photon, $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$, where p_i are classical probabilities. The density matrix formalism enables calculation of expectation values, decoherence dynamics, and entanglement measures such as concurrence.

Wigner function – a quasi-probability distribution in phase space that provides a complete description of a quantum state. Negative regions of the Wigner function are signatures of nonclassicality, often observed for Fock states or Schrödinger-cat states. The Wigner function is reconstructed experimentally via quantum state tomography.

Glauber-Sudarshan P representation – a decomposition of a density operator into a weighted integral over coherent states: $P = \int P(\alpha)\, |\alpha\rangle\langle\alpha|\, d^2\alpha$. Classical states have a well-behaved, positive $P(\alpha)$, while nonclassical states require singular or negative distributions, indicating the impossibility of a classical description.

Heisenberg picture – a formulation of quantum mechanics where operators evolve in time while the state vectors remain fixed. In quantum optics, the Heisenberg equations of motion for $\hat{a}$ and $\hat{a}^\dagger$ directly yield the dynamics of field quadratures, facilitating the analysis of squeezing and parametric amplification.

Schrödinger picture – the conventional formulation where the state vector evolves according to the time-dependent Schrödinger equation, while operators are static. This picture is useful for describing pulse propagation in the interaction picture and for solving master equations for open quantum systems.

Heisenberg uncertainty principle – the fundamental limit $\Delta X \Delta P \geq \hbar/2$ for the product of the variances of two conjugate observables (e.G., Position X and momentum P, or field quadratures $\hat{X}$ and $\hat{P}$). Squeezed states exploit this relation by reducing the variance of one quadrature at the cost of increasing the other.

Quadrature – the field components analogous to position and momentum, defined as $\hat{X} = (\hat{a} + \hat{a}^\dagger)/2$ and $\hat{P} = (\hat{a} - \hat{a}^\dagger)/(2i)$. Quadrature measurements are performed using homodyne detection, where the signal interferes with a strong local oscillator to extract phase-sensitive information.

Homodyne detection – a technique that mixes a weak signal with a strong, phase-locked local oscillator on a beam splitter, then measures the difference photocurrent. By varying the local oscillator phase, one can select any quadrature, enabling reconstruction of the Wigner function and verification of squeezing.

Heterodyne detection – similar to homodyne detection but uses a local oscillator offset in frequency, producing a beat note that contains both quadratures simultaneously. Heterodyne detection is useful for broadband spectral analysis and for measuring complex amplitudes of weak optical fields.

Single-photon detector – a device capable of registering the arrival of individual photons with high timing resolution. Common technologies include avalanche photodiodes (APDs), superconducting nanowire single-photon detectors (SNSPDs), and transition-edge sensors (TES). Each offers trade-offs among quantum efficiency, dark count rate, and timing jitter.

Avalanche photodiode (APD) – a semiconductor photodiode operated above its breakdown voltage, where a single photon triggers an avalanche of carriers, producing a macroscopic pulse. APDs are widely used for telecom-band detection but suffer from afterpulsing and limited quantum efficiency compared to SNSPDs.

Superconducting nanowire single-photon detector (SNSPD) – a thin superconducting wire biased near its critical current. Absorption of a photon locally destroys superconductivity, creating a resistive hotspot that yields a voltage pulse. SNSPDs offer $> 90\,\%$ quantum efficiency, low dark counts, and picosecond timing resolution, making them ideal for quantum communications.

Quantum key distribution (QKD) – a cryptographic protocol that uses quantum states to establish a shared secret key with unconditional security. The BB84 protocol, for instance, encodes bits in the polarization of single photons; any eavesdropping attempt inevitably introduces detectable errors due to the no-cloning theorem.

Quantum teleportation – the transfer of an unknown quantum state from one location to another using a pair of entangled photons and classical communication. The protocol requires a Bell-state measurement on the sender's side and appropriate unitary corrections on the receiver's side, enabling faithful reconstruction of the original state.

Quantum memory – a device that can store photonic quantum information for a controllable duration with high fidelity. Techniques include electromagnetically induced transparency (EIT) in atomic ensembles, off-resonant Raman protocols, and rare-earth-doped crystal memories. Quantum memories are essential for scalable quantum repeaters.

Photon blockade – a phenomenon in a strongly nonlinear cavity where the presence of one photon shifts the cavity resonance, preventing a second photon from entering. This effect leads to antibunching and enables deterministic single-photon sources and photon-photon gates.

Optical tweezers – tightly focused laser beams that exert gradient forces on dielectric particles, trapping and manipulating them. In quantum optics, tweezers can hold single atoms or quantum dots, enabling precise positioning for cavity QED or for assembling photonic circuits.

Optical lattice – a periodic potential for neutral atoms created by interfering laser beams. Atoms trapped in an optical lattice can emulate solid-state systems, realize Bose-Einstein condensates, and serve as a platform for quantum simulation of many-body physics.

Bose-Einstein condensate (BEC) – a macroscopic quantum state of dilute bosonic atoms cooled to near absolute zero, where a large fraction occupies the ground state. BECs provide a coherent matter wave source, enabling matter-wave interferometry and nonlinear optics analogues such as four-wave mixing.

Rydberg atoms – atoms excited to high principal quantum numbers, exhibiting strong dipole-dipole interactions and long lifetimes. In photonics, Rydberg excitations can mediate strong photon-photon interactions, leading to phenomena such as photon blockade and deterministic quantum gates.

Optical resonator – a structure that confines light by multiple reflections, forming standing-wave modes. Fabry-Pérot cavities consist of two mirrors separated by distance L; the resonance condition is $m\lambda = 2L$. The resonator's quality factor $Q = \nu/\Delta\nu$ quantifies energy storage versus loss.

Quality factor (Q) – a dimensionless parameter that measures the sharpness of a resonator's frequency response. High-Q resonators store photons for many optical cycles, enhancing light-matter interaction and enabling low-threshold lasers, narrowband filters, and cavity QED experiments.

Finesse – the ratio of the free spectral range to the linewidth of a resonator, essentially the same as Q for low-loss cavities. $\text{Finesse} = \pi\sqrt{R}/(1 - R)$ for a Fabry-Pérot cavity with mirror reflectivity R; high finesse implies low loss and long photon lifetimes.

Free spectral range (FSR) – the frequency spacing between adjacent longitudinal modes of a cavity, given by $\Delta\nu = c/2L$. The FSR determines the mode density and influences the design of frequency combs and multiplexed quantum channels.

Mode locking – a technique that forces the phases of longitudinal modes to lock together, producing a train of ultrashort pulses. Passive mode locking uses saturable absorbers; active mode locking employs external modulation. Mode-locked lasers are sources of femtosecond pulses for time-resolved spectroscopy.

Ultrafast laser – a laser that emits pulses with durations on the order of picoseconds or femtoseconds. Ultrafast lasers enable pump-probe experiments, high-harmonic generation, and precise control of quantum dynamics in solid-state and atomic systems.

Pump-probe spectroscopy – a time-resolved technique where a strong pump pulse excites a system, and a delayed probe pulse measures its response. By varying the delay, one can map relaxation dynamics, carrier recombination, and coherent phonon oscillations.

Four-wave mixing (FWM) – a χ^(3) nonlinear process where three photons interact to generate a fourth photon, satisfying energy and momentum conservation: $\Omega_1 + \omega_2 = \omega_3 + \omega_4$. FWM is exploited for wavelength conversion, parametric amplification, and generation of entangled photon pairs in fibers.

Raman scattering – inelastic scattering of photons by vibrational modes of a medium, resulting in Stokes (energy loss) and anti-Stokes (energy gain) photons. Stimulated Raman scattering can amplify signals and is used in Raman lasers and spectroscopy.

Brillouin scattering – a process where photons interact with acoustic phonons, leading to frequency shifts on the order of GHz. Stimulated Brillouin scattering is a limiting factor in high-power fiber systems but can also be harnessed for narrowband filtering and slow-light devices.

Kerr nonlinearity – the intensity-dependent refractive index change $n = n_0 + n_2 I$, where n_2 is the Kerr coefficient. The Kerr effect underlies self-phase modulation, cross-phase modulation, and soliton formation in fibers. It also enables all-optical switching.

Photonic integrated circuit (PIC) – a chip-scale platform that integrates multiple photonic components (waveguides, modulators, detectors) on a single substrate. Silicon photonics leverages CMOS fabrication to create dense, low-cost optical interconnects for data centers and quantum processors.

Silicon photonics – the use of silicon as a waveguide material for photonic integration, exploiting its high refractive index contrast and mature fabrication infrastructure. Silicon's χ^(3) nonlinearity enables on-chip four-wave mixing and frequency comb generation.

Waveguide coupler – a device that transfers power between adjacent waveguides. Directional couplers exploit evanescent coupling; the coupling length determines the fraction of power transferred. Couplers form the basis of Mach-Zehnder interferometers and beam splitters in integrated circuits.

Directional coupler – a specific type of waveguide coupler where two parallel waveguides exchange energy through evanescent fields. By adjusting the interaction length, one can achieve 50:50 Splitting, essential for balanced interferometers and quantum logic gates.

Mach-Zehnder interferometer (MZI) – a two-arm interferometer where light is split, phase-shifted in each arm, and recombined. The output intensity depends on the relative phase, allowing precise phase modulation, switching, and sensing. Integrated MZIs are key components in photonic quantum processors.

Sagnac interferometer – an interferometer where counter-propagating beams travel a closed loop, recombining to produce interference. It is inherently stable against environmental perturbations and is used in fiber-optic gyroscopes and quantum communication schemes.

Fabry-Pérot interferometer – a resonant cavity formed by two partially reflecting mirrors. The transmission spectrum consists of periodic peaks whose width is set by the finesse. Fabry-Pérot filters are employed for wavelength selection in lasers and for high-resolution spectroscopy.

Optical coherence tomography (OCT) – an imaging technique that uses low-coherence interferometry to obtain depth-resolved images of scattering media. OCT relies on broadband light sources and measures the interference between reference and sample arms, providing micron-scale axial resolution.

Quantum metrology – the use of quantum states of light (e.G., Squeezed or entangled photons) to improve measurement precision beyond classical limits. The Heisenberg limit scales as $1/N$, where N is the number of photons, compared to the shot-noise limit $1/\sqrt{N}$.

Heisenberg limit – the ultimate precision bound achievable with N entangled particles, giving an uncertainty scaling of $\Delta\theta \propto 1/N$. Achieving this limit requires highly entangled states such as NOON states, which are challenging to generate and fragile to loss.

Shot noise – the fundamental quantum noise arising from the discrete nature of photons. In a coherent state, the variance of the photon number equals the mean, leading to a signal-to-noise ratio that scales as $\sqrt{\langle n \rangle}$. Shot noise sets the standard quantum limit for many measurements.

Quantum noise – the intrinsic fluctuations associated with quantum operators, including vacuum fluctuations and photon-number noise. Quantum noise can be reduced in certain quadratures via squeezing, enabling measurements below the shot-noise limit.

Decoherence – the loss of quantum coherence due to interaction with the environment, leading to the transition from a pure state to a mixed state. In photonic systems, decoherence arises from scattering, absorption, and phase noise, limiting entanglement distribution.

Dephasing – a specific type of decoherence where the relative phase between components of a superposition randomizes, while populations remain unchanged. Dephasing is modeled by a pure-dephasing Lindblad term in the master equation and manifests as line broadening.

Quantum trajectory – a stochastic method for simulating the evolution of an open quantum system conditioned on measurement outcomes. The Monte Carlo wave-function approach generates individual “trajectories” that, when averaged, reproduce the master-equation dynamics.

Master equation – a differential equation governing the time evolution of the density matrix of an open system. The Lindblad form provides a completely positive, trace-preserving description: $D\rho/dt = -i[\hat{H}, \rho] + \sum_k \gamma_k (\hat{L}_k \rho \hat{L}_k^\dagger - \frac{1}{2}\{\hat{L}_k^\dagger \hat{L}_k, \rho\})$.

Lindblad form – the standard structure of Markovian master equations that ensures physicality. The operators $\hat{L}_k$ represent environmental channels (e.G., Spontaneous emission, cavity decay) with rates γ_k. This form is widely used to model dissipation in cavity QED and waveguide QED.

Optical Bloch equations – a set of equations describing the dynamics of a two-level atom interacting with a coherent field, incorporating relaxation and dephasing. They capture phenomena such as Rabi oscillations, power broadening, and saturation, and are the foundation for laser spectroscopy analysis.

Rabi oscillations – coherent oscillations of a two-level system’s population under resonant driving, with frequency $\Omega_R = \mu E/\hbar$ (μ is the dipole moment, E the field amplitude). Observation of Rabi oscillations in a quantum dot verifies strong coupling and coherent control.

Dressed states – eigenstates of the combined atom-field system in the strong-coupling regime, formed by superpositions of atomic and photonic excitations. The energy splitting between dressed states is the vacuum Rabi splitting, observable in transmission spectra of high-Q cavities.

Purcell effect – the modification of an emitter’s spontaneous emission rate due to its environment, quantified by the Purcell factor $F_P = (3/4\pi^2)(\lambda/n)^3 (Q/V)$. High-Q, low-V cavities enhance emission into a desired mode, enabling efficient single-photon sources.

Photonic bandgap – a frequency range in a photonic crystal where propagation is prohibited. By introducing a defect, one creates a localized mode within the bandgap, offering a high-Q cavity without the need for mirrors. This design is used for integrated lasers and cavity QED experiments.

Non-Hermitian Hamiltonian – an effective Hamiltonian that includes loss or gain terms, often written $\hat{H}_{eff} = \hat{H} - i(\kappa/2)\hat{a}^\dagger\hat{a}$ for a cavity with decay rate κ. Non-Hermitian descriptions simplify analysis of open systems and can predict exceptional points in PT-symmetric photonics.

Parity-time (PT) symmetry – a concept where balanced gain and loss lead to real eigenvalues despite a non-Hermitian Hamiltonian. PT-symmetric photonic structures exhibit unusual phenomena such as loss-induced transparency and unidirectional invisibility.

Optical frequency comb – a spectrum consisting of equally spaced lines, generated by mode-locked lasers or microresonator Kerr combs. Frequency combs provide precise rulers for spectroscopy, metrology, and coherent optical communications.

Microresonator Kerr comb – a compact resonator that, under continuous-wave pumping, exploits the Kerr nonlinearity to generate a comb via four-wave mixing. The resulting comb lines can be stabilized to form a chip-scale optical clock.

Quantum dot-cavity system – a platform where a single quantum dot is embedded in a photonic crystal cavity, enabling strong coupling and Purcell enhancement. This system serves as a deterministic single-photon source, a node for quantum networks, and a testbed for cavity QED.

Integrated quantum photonic circuit – a chip that combines sources, waveguides, interferometers, and detectors to process quantum information. Demonstrations include on-chip boson sampling, entanglement generation, and quantum error correction using linear optics.

Linear optics quantum computing (LOQC) – a model of quantum computation that uses only linear optical elements (beam splitters, phase shifters) together with measurement-induced nonlinearity. The KLM protocol showed that LOQC is universal, albeit with high resource overhead.

Boson sampling – a computational problem where indistinguishable photons are sent through a random linear optical network, and the output distribution is sampled. Boson sampling is believed to be hard for classical computers, providing a near-term demonstration of quantum advantage.

Quantum walk – the quantum analogue of a classical random walk, implemented in photonic lattices or waveguide arrays. Quantum walks exhibit faster spreading and have applications in quantum algorithms, simulation of topological phases, and transport studies.

Topological photonics – the study of photonic structures that emulate topological insulators, supporting edge states immune to backscattering. These states can transport light around sharp corners with low loss, offering robust routing for on-chip communication.

Exceptional point – a degeneracy in a non-Hermitian system where both eigenvalues and eigenvectors coalesce. Near an exceptional point, small parameter changes induce large spectral shifts, enabling ultra-sensitive sensors based on PT-symmetric resonators.

Quantum non-demolition (QND) measurement – a measurement that extracts information about a quantum observable without disturbing its subsequent evolution. In optics, QND measurements of photon number can be realized using cross-Kerr interactions, enabling photon-counting without absorption.

Cross-Kerr nonlinearity – a $\chi^{(3)}$ process where the intensity of one optical mode induces a phase shift on another mode, described by Hamiltonian $\hat{H} = \hbar\chi \hat{a}^{\dagger}\hat{a} \hat{b}^{\dagger}\hat{b}$. While naturally weak, engineered platforms (e.G., Atomic ensembles or superconducting circuits) aim to amplify this interaction for photonic gates.

All-optical switching – a device where one light beam controls another, using nonlinear effects such as Kerr-induced phase shift or two-photon absorption. All-optical switches are key for ultrafast routing in photonic networks and for creating deterministic photon-photon interactions.

Optical parametric oscillator (OPO) – a resonant cavity containing a $\chi^{(2)}$ nonlinear crystal, pumped above threshold to generate coherent signal and idler beams. OPOs provide tunable coherent sources in the mid-infrared and are used for squeezed-light generation.

Entangled photon source – a system that produces photon pairs in a nonseparable quantum state. Common implementations include type-II PDC in periodically poled crystals and four-wave mixing in silicon waveguides. Bright, low-noise sources are essential for scaling quantum communication.

Wavelength-division multiplexing (WDM) – a technique that transmits multiple optical channels at different wavelengths over a single fiber. In quantum networks, WDM allows parallel distribution of entangled photon pairs, increasing channel capacity while requiring careful management of crosstalk.

Frequency conversion – the process of shifting photon frequency while preserving quantum properties. Techniques include sum-frequency generation, difference-frequency generation, and quantum frequency conversion using nonlinear waveguides. Frequency conversion bridges the gap between telecom-band transmission and visible-band quantum memories.

Quantum repeaters – architectures that extend the range of quantum communication by dividing the channel into segments, storing entanglement in quantum memories, and performing entanglement swapping. Repeaters mitigate loss and decoherence, enabling continent-scale quantum networks.

Entanglement swapping – a protocol where two independently entangled photon pairs are combined at a Bell-state measurement, resulting in entanglement between distant photons that never interacted. This operation is a core component of quantum repeaters and teleportation networks.

Decoy-state method – a technique in QKD that varies the intensity of transmitted pulses to detect photon-number-splitting attacks. By comparing detection statistics of signal and decoy states, the legitimate parties can bound the eavesdropper's information.

Device-independent QKD – a security approach that does not rely on trusting the internal workings of the devices, but instead bases security on violation of Bell inequalities. This method provides robustness against side-channel attacks and faulty components.

Quantum error correction (QEC) – a set of protocols that protect quantum information from decoherence by encoding logical qubits into entangled physical qubits. In photonic platforms, QEC codes such as the bosonic cat code and surface code have been demonstrated using squeezed states and cluster states.

Cluster state – a highly entangled multi-qubit state that serves as a resource for measurement-based quantum computation. Photonic cluster states are generated by entangling photons via fusion gates or by using nonlinear interactions in waveguide arrays.

Fusion gate – an operation that joins two smaller photonic entangled states into a larger one, typically using beam splitters and post-selection. Fusion gates enable scalable construction of large cluster states for LOQC.

Time-bin encoding – a method of representing quantum information in the arrival times of photons, using early and late time slots as logical basis states. Time-bin qubits are robust against polarization drift in fibers and are widely used in long-distance QKD.

Quantum dot-based single-photon source – a solid-state emitter that can be triggered electrically or optically to emit one photon on demand. Purcell enhancement in a cavity improves extraction efficiency, while resonant excitation reduces multi-photon emission probability.

Multiplexed single-photon source – an architecture that combines several probabilistic sources (e.G., SPDC) with fast optical switches and feed-forward control to increase the probability of delivering a single photon on demand. Multiplexing improves scalability for photonic quantum computing.

Superconducting quantum interference device (SQUID) – a superconducting loop with Josephson junctions, used as a highly sensitive magnetic flux detector. In the context of photonics, SQUIDs can read out microwave photons from superconducting resonators, forming a bridge between optical and microwave quantum technologies.

Microwave-optical transducer – a device that converts photons between microwave and optical frequencies, often using electro-optomechanical coupling. Efficient transduction is a key challenge for integrating superconducting qubits with optical quantum networks.

Quantum optomechanics – the study of the interaction between light and mechanical motion at the quantum level. In cavity optomechanics, the radiation pressure couples an optical mode to a mechanical resonator, enabling ground-state cooling, entanglement generation, and quantum-limited sensing.

Ground-state cooling – the process of reducing a mechanical resonator's phonon occupation to near zero, typically via sideband cooling in an optomechanical cavity. Achieving the ground state allows observation of quantum effects in macroscopic objects.

Sideband asymmetry – a signature of quantum motion where the Stokes and anti-Stokes scattering rates differ, reflecting the imbalance between phonon creation and annihilation. Measurement of sideband asymmetry provides a thermometry method for mechanical resonators.