LIGHT-MATTER INTERACTION AT THE SUB-WAVELENGTH SCALE

NANOPHOTONICS

Dielectric Nanostructures, Plasmonics, and Purcell Enhancement

An axiomatic guide detailing sub-wavelength confinement, localized optical modes, and structural field control.

1. BREAKING THE CLASSICAL DIFFRACTION LIMIT

In classical optics, Ernst Abbe's diffraction limit restricts the minimum spatial focal spot size of a light wave traveling in a medium with refractive index n:

$$\Delta x \approx \frac{\lambda}{2 \cdot \mathrm{NA}} = \frac{\lambda}{2n \sin\theta}$$

Nanophotonics bypasses this fundamental boundary by trapping light within **evanescent near-fields** instead of propagating far-fields. This localizes electromagnetic energy down to deep sub-wavelength scales ($V \ll \lambda^3$).

2. MODIFYING EMISSION: THE PURCELL EFFECT

Spontaneous emission is not an intrinsic properties of an atom or qubit; it is governed by the structural environment (local density of optical states, LDOS). Nanophotonic cavities accelerate emission via the **Purcell Factor** (F_P):

The Purcell Factor Formulation: When an emitter matches the cavity resonance frequency ($\omega_e = \omega_c$), its spontaneous emission rate enhancements scales as:

$$F_P = \frac{\Gamma_{\mathrm{cav}}}{\Gamma_{\mathrm{bulk}}} = \frac{3}{4\pi^2} \left(\frac{\lambda}{n}\right)^3 \left(\frac{Q}{V_{\mathrm{mode}}}\right)$$

Where: $Q = \omega_c / \delta\omega$ is the cavity quality factor, and V_{mode} is the mode volume.
The Optimization Trade-off: High F_P requires scaling up the structural photon lifetime (Q) or shrinking the physical path profile (V_{mode}).

3. ENGINEERING MODALITIES: PLASMONICS VS. DIELECTRICS

To alter local field metrics, nanophotonic components divide into two distinct structural design configurations:

- **Plasmonics (Surface Plasmon Resonances):** Couples light to collective free-electron oscillations at metal-dielectric boundaries (e.g., gold or silver particles). This forces an extreme compression of V_{mode}, yielding massive F_P values despite low Q factors due to inherent metallic absorption losses ($\epsilon_{\mathrm{metal}} = \epsilon' + i\epsilon''$).
- **High-Index Dielectrics (Mie Resonances):** Leverages low-loss materials (e.g., Silicon, TiO_2). These structures support both electric and magnetic dipoles simultaneously without thermal dissipative decay, maintaining high Q profiles.

4. STRUCTURAL LIGHT MANIPULATION PLATFORMS

By pattern-mapping materials at sub-wavelength resolutions, light can be steered along arbitrary physical paths:

PHOTONIC CRYSTALS AND METASURFACES

Photonic crystals periodically alter the refractive index to open a **Photonic Bandgap**, forbidding certain photon energies from propagating—analogous to electronic semiconductor bands.

Metasurface Phase Discontinuity Law: $\Delta\Phi(x, y) = \vec{k}_{\mathrm{out}} \cdot \vec{r} - \vec{k}_{\mathrm{in}} \cdot \vec{r}$

Flat Optics Convergence: Flat 2D metasurfaces use arrays of sub-wavelength nano-antennas (meta-atoms) to abruptly alter the amplitude, phase, and polarization of light, completely replacing bulky classical lenses.

5. CHIRAL QUANTUM NANOPHOTONICS

When emitters couple to asymmetric nanophotonic structures (like photonic crystal waveguides), the local field exhibits high **transverse spin density**. This ties the circular polarization of the photon directly to its physical propagation path:

$$\vec{k} \to +x \implies \sigma_+ \text{ (Right)} \qquad \text{and} \qquad \vec{k} \to -x \implies \sigma_- \text{ (Left)}$$

This spin-momentum locking creates non-reciprocal, unidirectional quantum channels, preventing standard back-scattering and shielding multi-qubit cascade links.