

Complete Optics

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1 The Nature of Light

1.1 Core ideas

Optics studies light as rays, waves, photons, and electromagnetic fields. Which model is useful depends on scale: rays work when wavelengths are tiny, waves explain interference and diffraction, and photons explain detection, emission, and quantum noise.

For review, be able to choose the right model for a problem, relate frequency, wavelength, and energy, and connect intensity to field amplitude. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

1.2 Mathematical spine

$$c = \lambda\nu, \quad E_\gamma = h\nu, \quad I = \frac{1}{2}c\epsilon_0 E_0^2$$

Section summary Light is one phenomenon with ray, wave, field, and photon descriptions.

2 Geometrical Optics

2.1 Core ideas

Geometrical optics follows rays through reflection, refraction, mirrors, and lenses. Fermat's principle says rays make optical path length stationary. Paraxial approximations give simple imaging formulas, magnification, apertures, aberrations, and optical instruments.

For review, be able to use Snell's law, draw ray diagrams, apply lens and mirror equations, and know when the paraxial approximation fails. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

2.2 Mathematical spine

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \quad \frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

Section summary Ray optics is the short-wavelength limit of wave optics.

3 Wave Propagation

3.1 Core ideas

Wave optics treats light as fields satisfying wave equations. Plane waves, spherical waves, phase velocity, group velocity, impedance, and dispersion describe propagation. Boundary conditions at interfaces determine reflection, transmission, and evanescent waves.

For review, be able to derive plane-wave relations, compute phase accumulation, distinguish phase and group velocity, and apply boundary matching. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

3.2 Mathematical spine

$$\nabla^2 \mathbf{E} - \frac{n^2}{c^2} \partial_t^2 \mathbf{E} = 0, \quad \mathbf{E} = \mathbf{E}_0 e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}$$

Section summary Wave propagation is controlled by phase, boundary conditions, and dispersion.

4 Superposition of Waves

4.1 Core ideas

Linear optics is based on superposition. Adding waves explains beats, standing waves, wave packets, normal modes, and interference. Phase relationships matter as much as amplitudes, so complex notation is the natural bookkeeping system.

For review, be able to add complex amplitudes, compute beats and standing waves, form wave packets, and interpret group velocity. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

4.2 Mathematical spine

$$E_1 + E_2 = E_{01}e^{i\phi_1} + E_{02}e^{i\phi_2}, \quad I \propto |E_1 + E_2|^2$$

Section summary Most optical structure comes from coherent superposition.

5 Polarization

5.1 Core ideas

Polarization is the vector state of the transverse electric field. Linear, circular, and elliptical polarization describe different phase relations between orthogonal components. Polarizers, wave plates, birefringent media, and Jones vectors provide practical control.

For review, be able to use Jones vectors, identify circular and linear polarization, compute Malus' law, and understand birefringent phase delay. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

5.2 Mathematical spine

$$\mathbf{E}(t) = \text{Re} \left[(E_x \hat{\mathbf{x}} + E_y e^{i\delta} \hat{\mathbf{y}}) e^{-i\omega t} \right], \quad I = I_0 \cos^2 \theta$$

Section summary Polarization is the vector degree of freedom of light.

6 Interference

6.1 Core ideas

Interference measures phase difference. Young's experiment, Michelson interferometers, thin films, and Fabry–Perot cavities all compare optical paths. Visibility depends on coherence, amplitude balance, and phase stability.

For review, be able to compute fringe spacing, thin-film phase shifts, optical path difference, and interferometer sensitivity. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

6.2 Mathematical spine

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta L, \quad I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \Delta\phi$$

Section summary Interference converts phase differences into intensity patterns.

7 Diffraction

7.1 Core ideas

Diffraction appears when apertures or obstacles are comparable to wavelength. Huygens–Fresnel ideas, Fraunhofer diffraction, single slits, gratings, and circular apertures explain resolution limits and beam spreading.

For review, be able to calculate basic diffraction patterns, use grating equations, estimate angular resolution, and distinguish near-field from far-field diffraction. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

7.2 Mathematical spine

$$a \sin \theta = m\lambda, \quad d \sin \theta = m\lambda, \quad \theta_{\text{Rayleigh}} \approx 1.22\lambda/D$$

Section summary Diffraction sets the wave limit of imaging and beam focusing.

8 Fourier Optics

8.1 Core ideas

Fourier optics treats propagation and imaging as spatial-frequency filtering. A lens maps angles to positions in its focal plane, making diffraction patterns and transfer functions natural. This explains resolution, filtering, convolution, and coherent imaging.

For review, be able to interpret apertures as filters, use Fourier transforms for far-field patterns, and connect point-spread functions to resolution. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

8.2 Mathematical spine

$$U_{\text{far}}(k_x, k_y) \propto \mathcal{F}\{U(x, y)\}, \quad I_{\text{image}} = |h * U_{\text{object}}|^2$$

Section summary Optical systems process spatial frequencies.

9 Coherence

9.1 Core ideas

Coherence measures how stable phase relationships are across time and space. Temporal coherence is tied to bandwidth; spatial coherence is tied to source size. Coherence functions explain fringe visibility, lasers, thermal light, and imaging contrast.

For review, be able to estimate coherence time and length, relate bandwidth to coherence, and explain visibility loss. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

9.2 Mathematical spine

$$\tau_c \sim \frac{1}{\Delta\nu}, \quad \ell_c \sim c\tau_c, \quad V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Section summary Coherence determines whether interference survives averaging.

10 Lasers and Modern Optics

10.1 Core ideas

Lasers use stimulated emission and optical feedback to produce coherent, narrow-band, directional light. Population inversion, gain, threshold, cavity modes, linewidth, nonlinear optics, fibers, and photodetectors form the toolbox of modern optical experiments.

For review, be able to explain stimulated emission, threshold, cavity modes, Gaussian beams, and the difference between spontaneous and laser light. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

10.2 Mathematical spine

$$gL \geq \alpha_{\text{loss}}, \quad \Delta\nu_{\text{FSR}} = \frac{c}{2nL}, \quad w(z) = w_0 \sqrt{1 + (z/z_R)^2}$$

Section summary Lasers make controlled coherent light for measurement, communication, and quantum experiments.