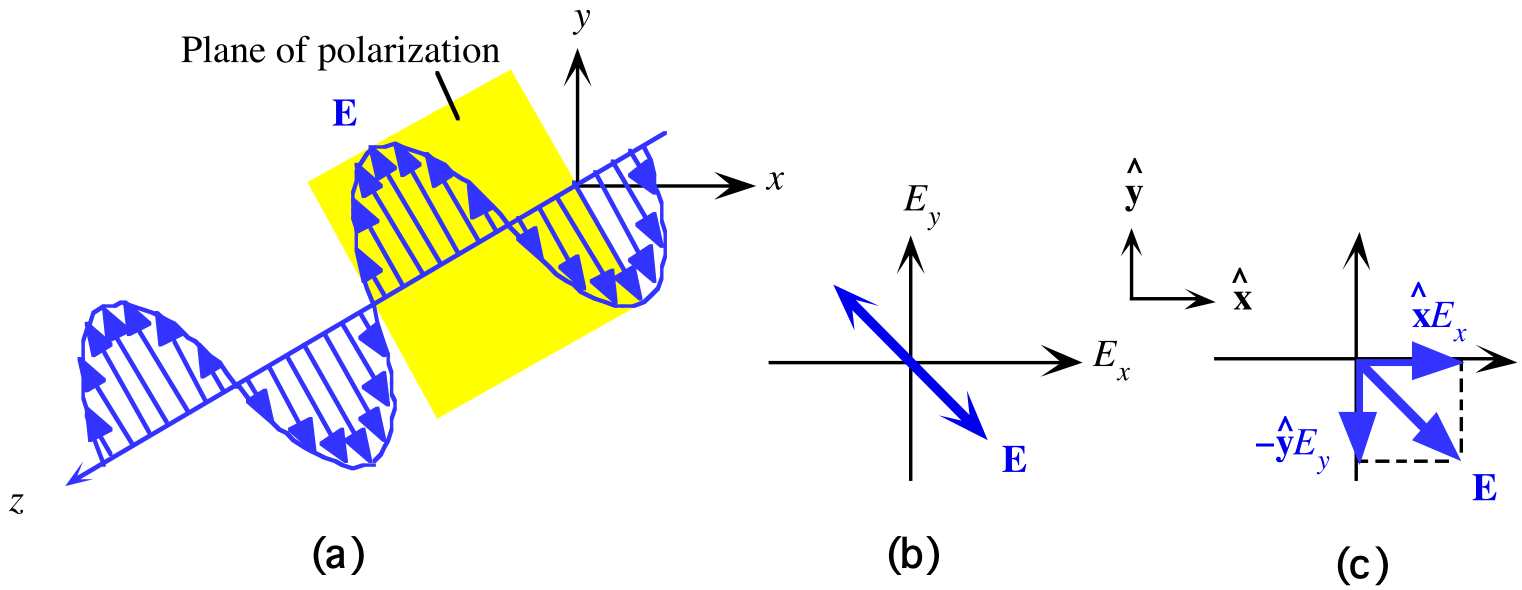
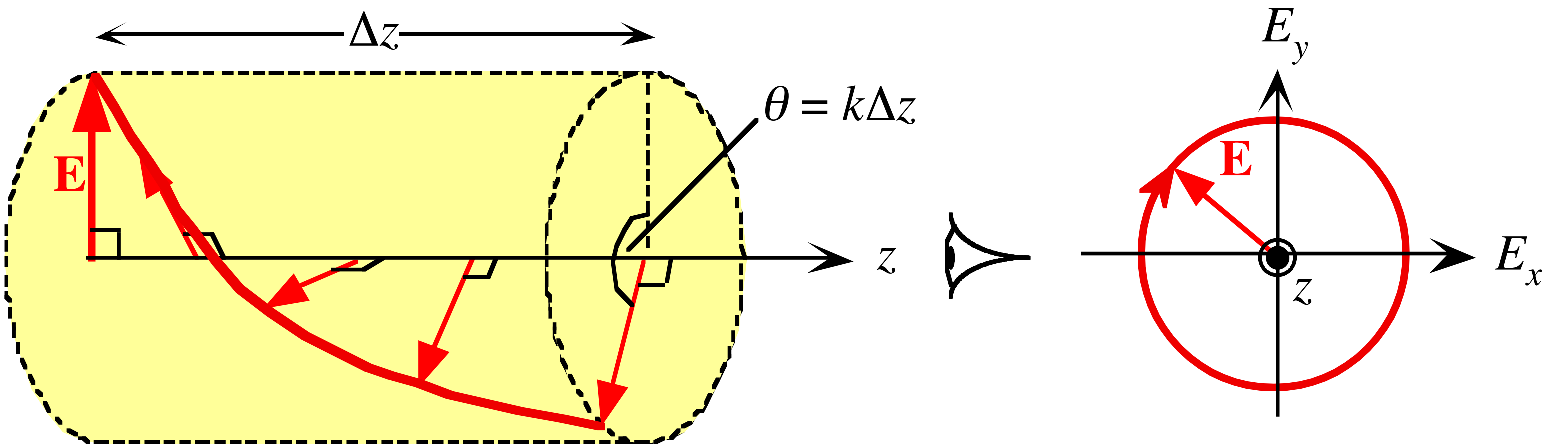
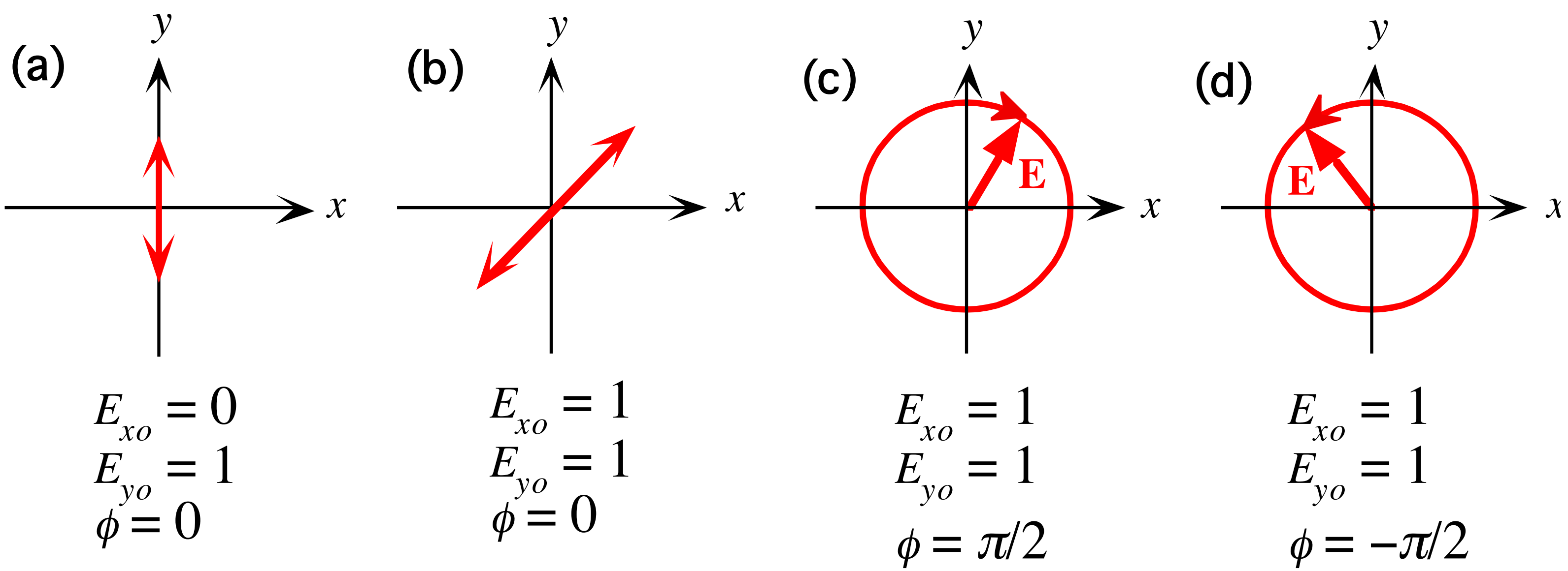


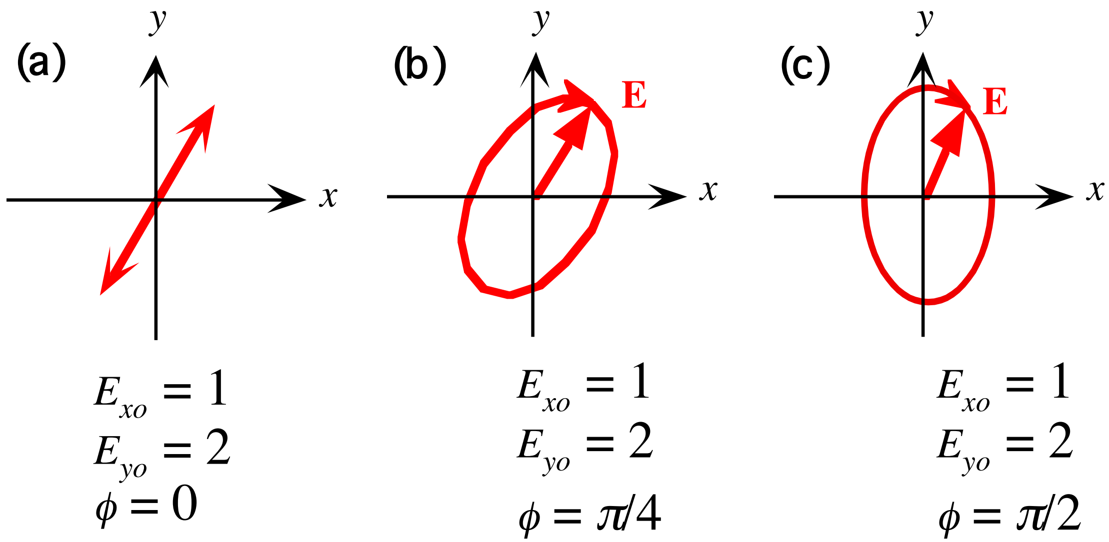
(a) A linearly polarized wave has its electric field oscillations defined along a line perpendicular to the direction of propagation, z. The field vector **E** and z define a *plane of polarization*. (b) The E-field oscillations are contained in the plane of polarization. (c) A linearly polarized light at any instant can be represented by the superposition of two fields E_x and E_y with the right magnitude and phase.



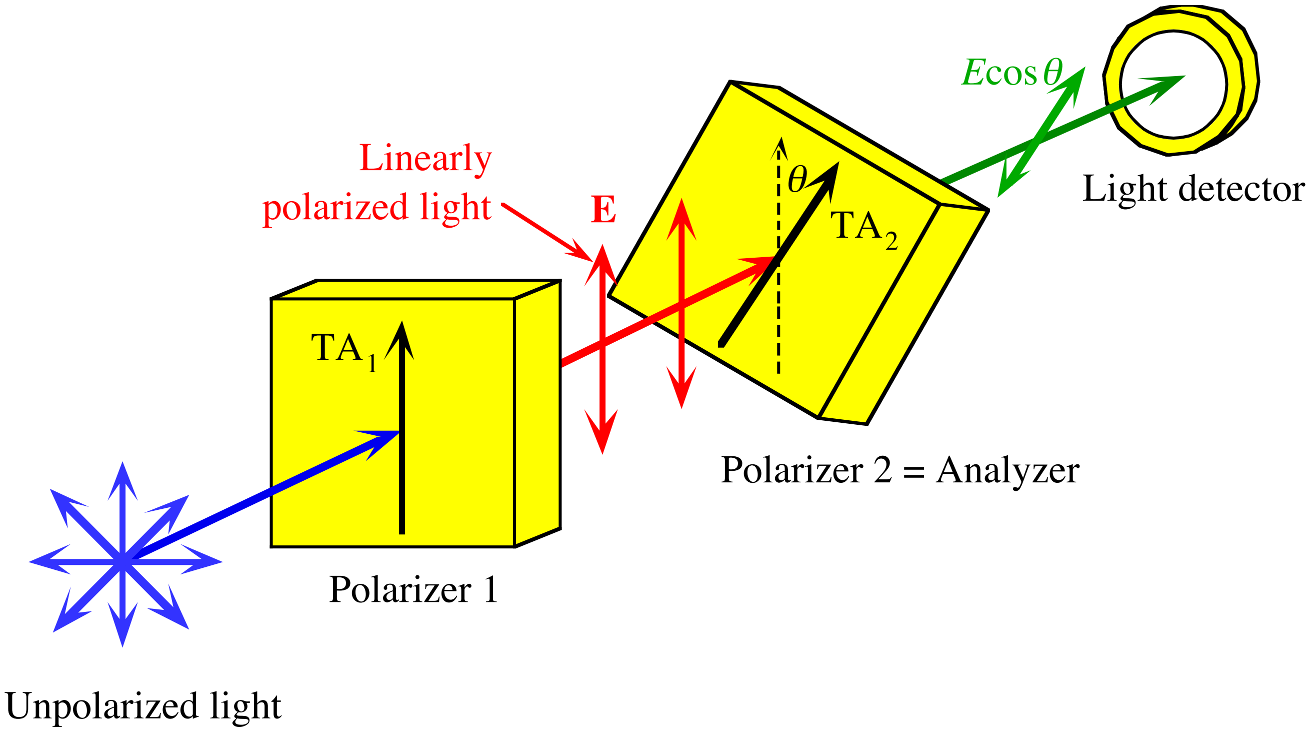
A *right circularly polarized light*. The field vector **E** is always at right angles to z , rotates clockwise around z with time, and traces out a full circle over one wavelength of distance propagated.



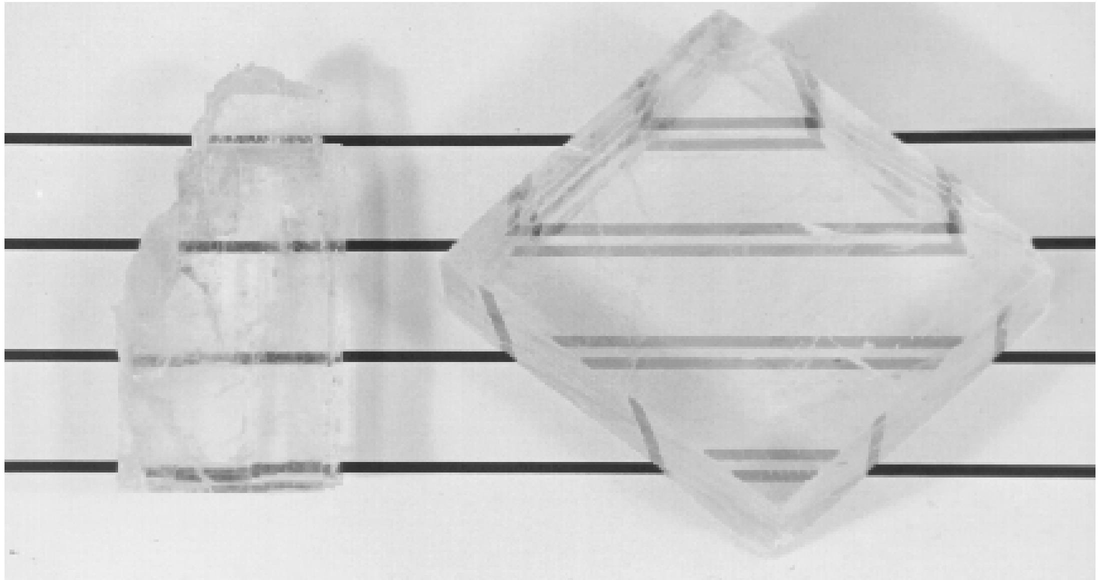
Examples of linearly, (a) and (b), and circularly polarized light (c) and (d); (c) is right circularly and (d) is left circularly polarized light (as seen when the wave directly approaches a viewer)



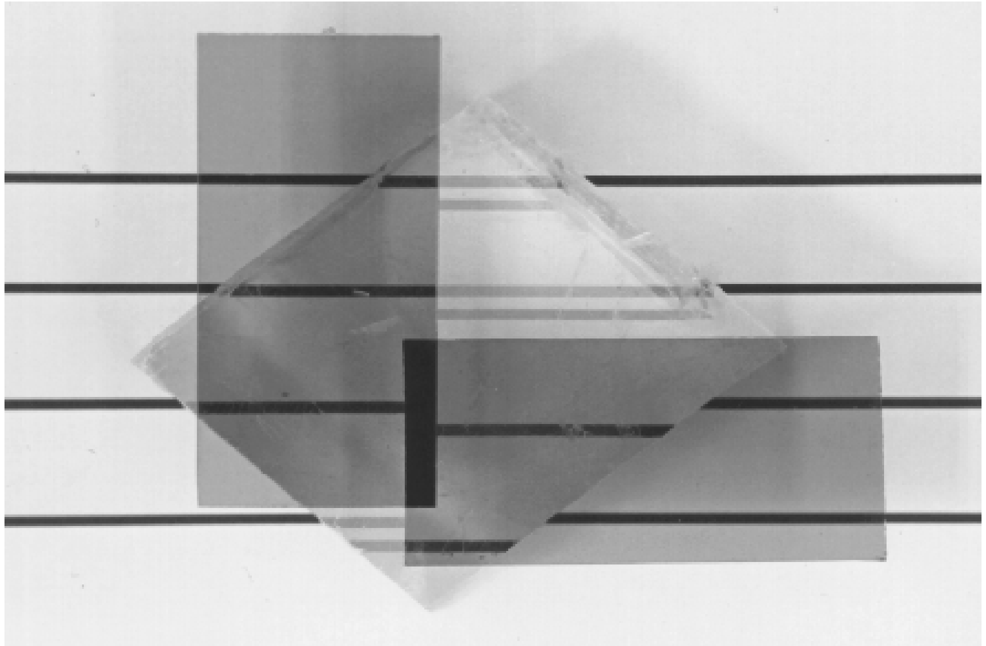
(a) Linearly polarized light with $E_{yo} = 2E_{xo}$ and $\phi = 0$. (b) When $\phi = \pi/4$ (45°), the light is right elliptically polarized with a tilted major axis. (c) When $\phi = \pi/2$ (90°), the light is right elliptically polarized. If E_{xo} and E_{yo} were equal, this would be right circularly polarized light.



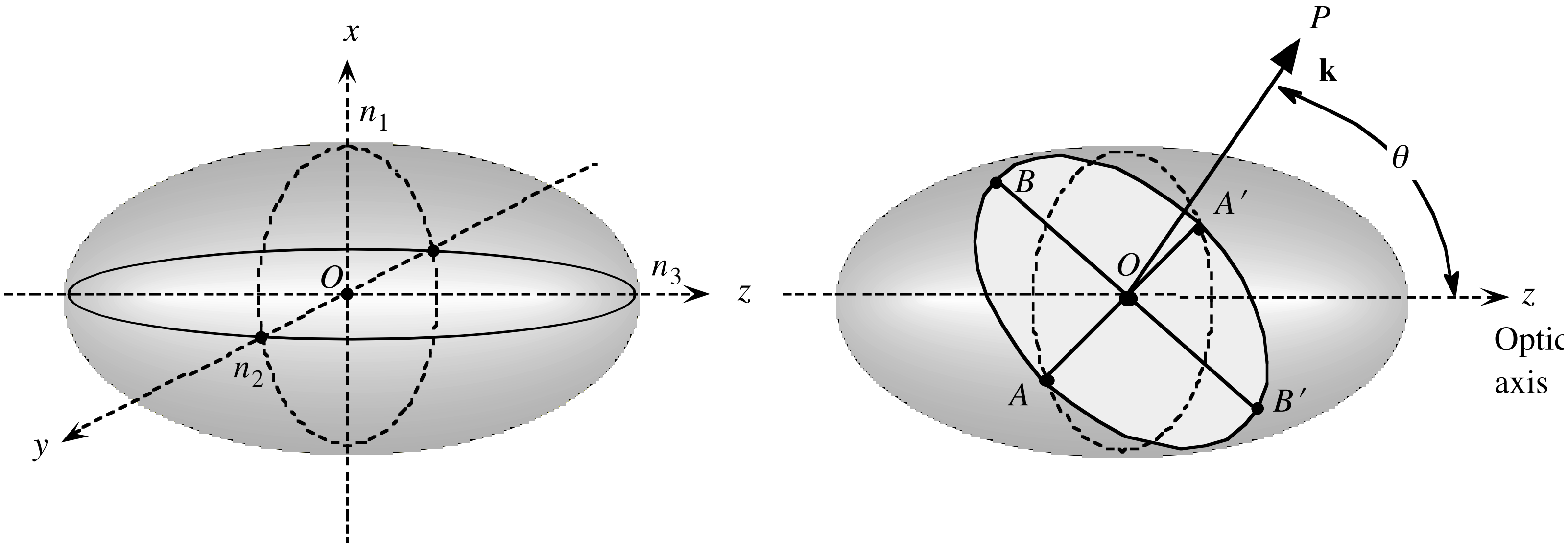
Randomly polarized light is incident on a Polarizer 1 with a transmission axis TA_1. Ligh emerging from Polarizer 1 is linearly polarized with **E** along TA_1, and becomes incident on Polarizer 2 (called "analyzer") with a transmission axis TA_2 at an angle θ to TA_1. A detector measures the intensity of the incident light. TA_1 and TA_2 are normal to the light direction.



A line viewed through a cubic sodium chloride (halite) crystal (optically isotropic) and a calcite crystal (optically anisotropic).

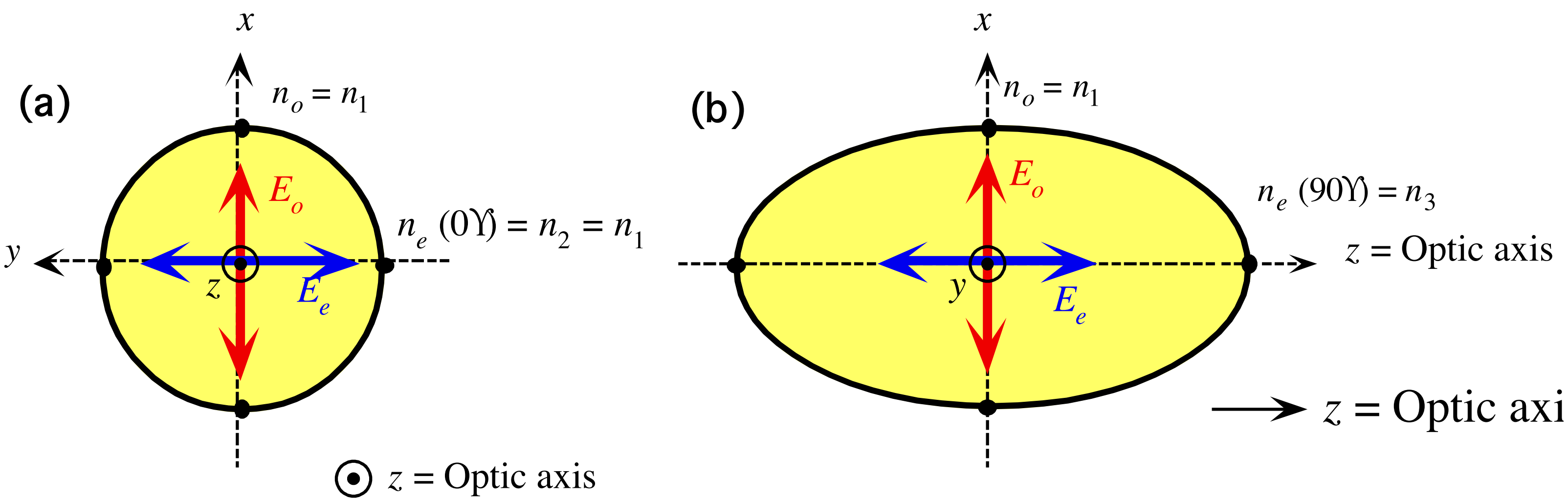


Two polaroid analyzers are placed with their transmission axes, along the long edges, at right angles to each other. The ordinary ray, undeflected, goes through the left polarizer whereas the extraordinary wave, deflected, goes through the right polarizer. The two waves therefore have orthogonal polarizations.

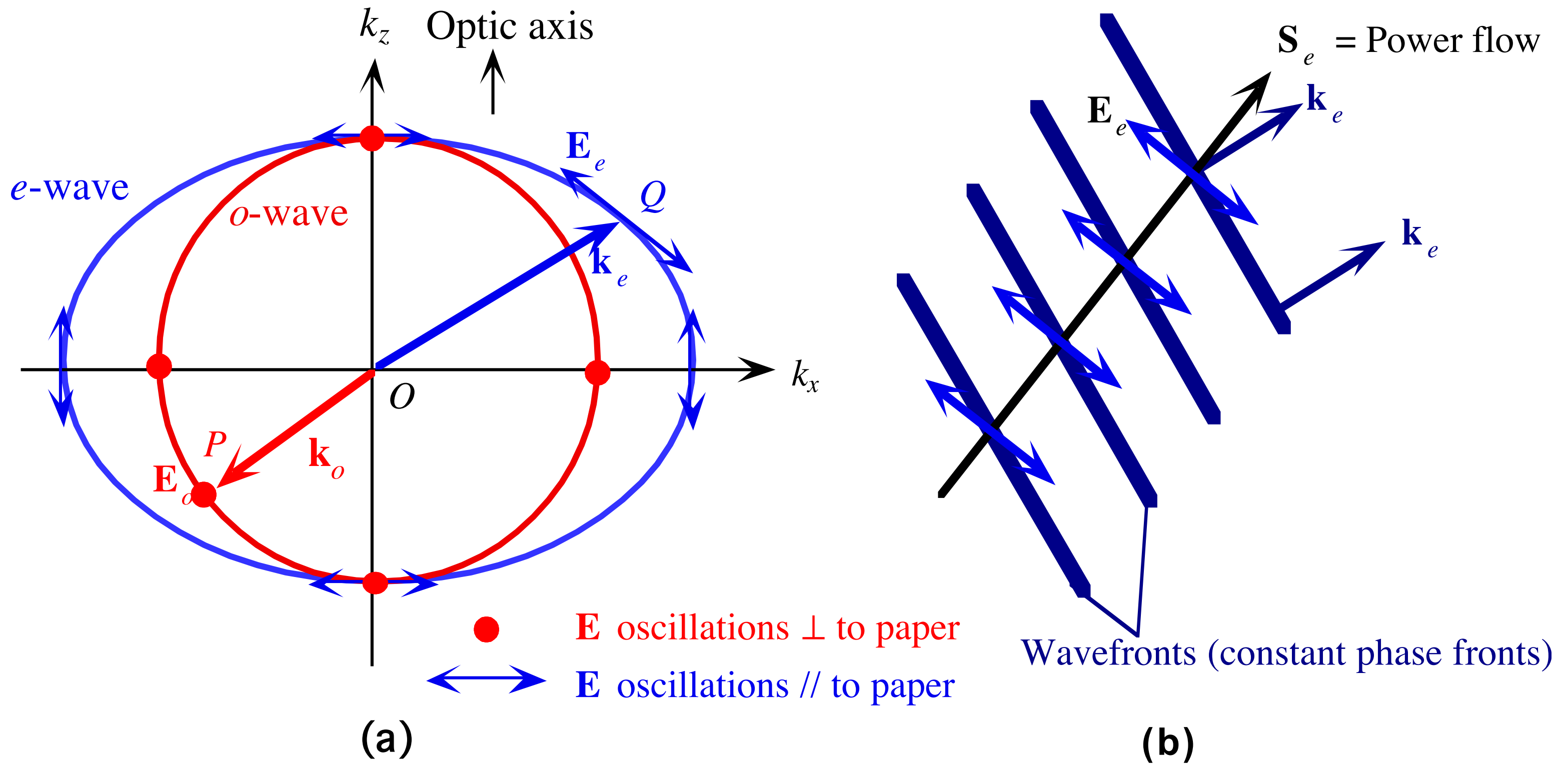


(a) Fresnel's ellipsoid

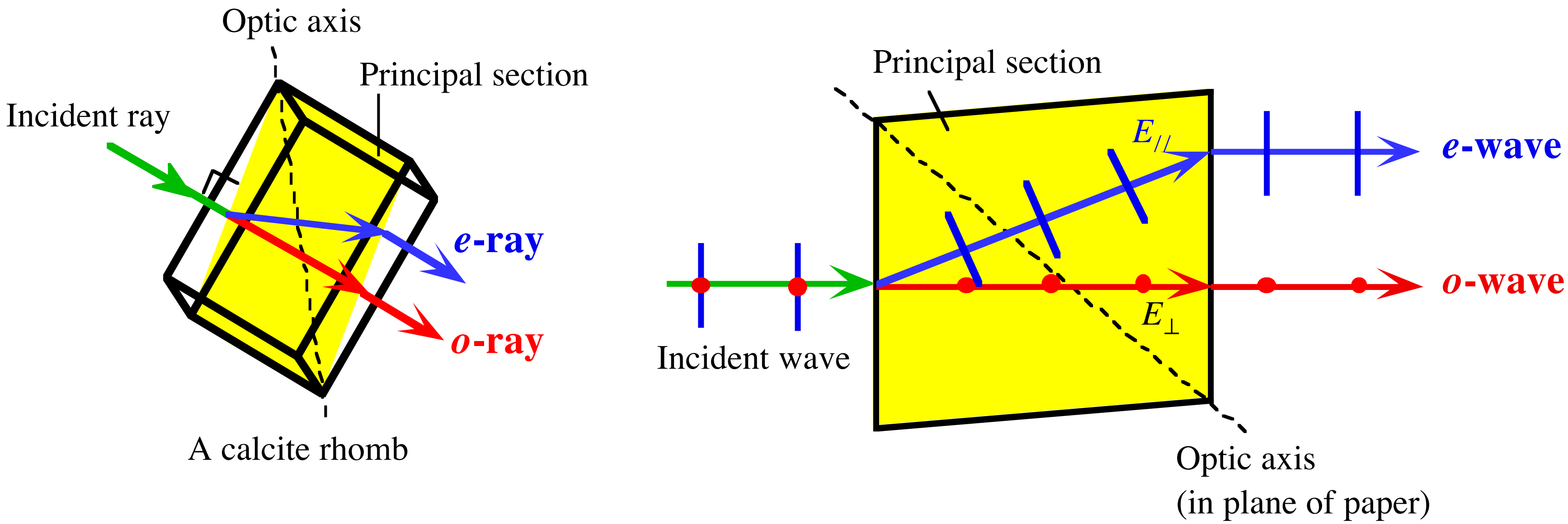
(b) An EM wave propagating along *OP* at an angle θ to optic axis.



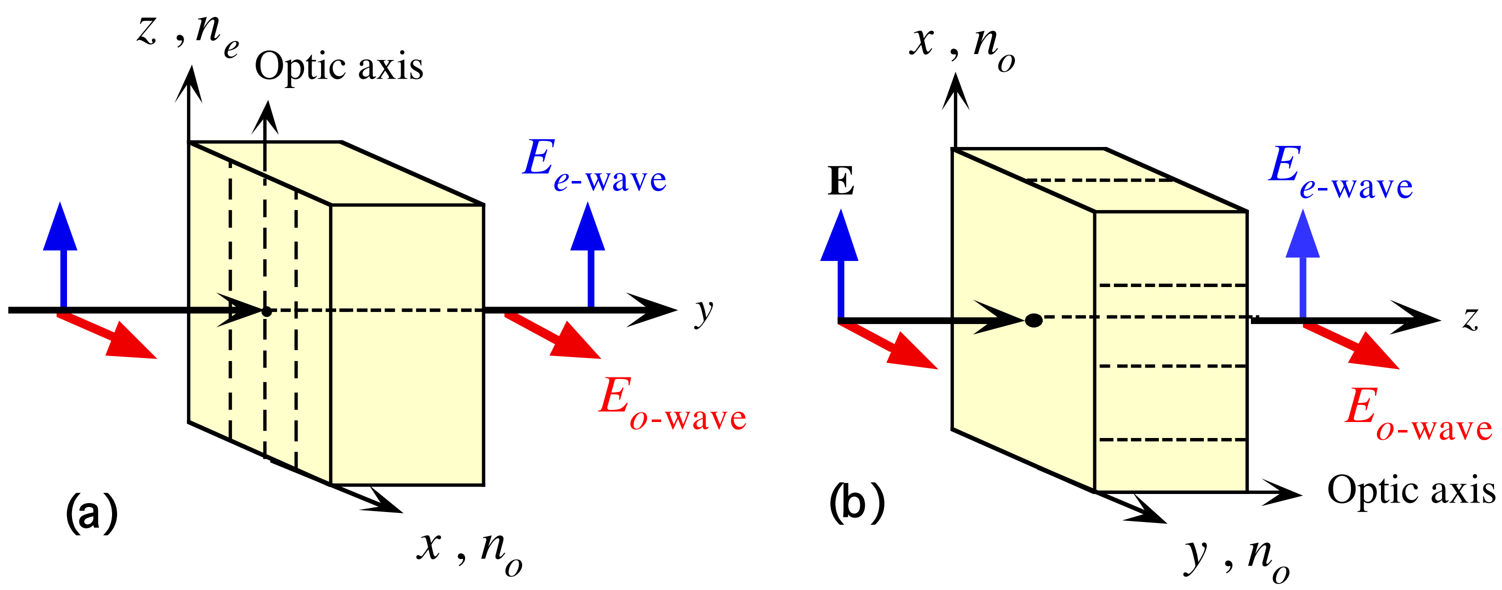
$E_o = E_{o\text{-wave}}$ and $E_e = E_{e\text{-wave}}$ (a) Wave propagation along the optic axis. (b) Wave propagation normal to optic axis



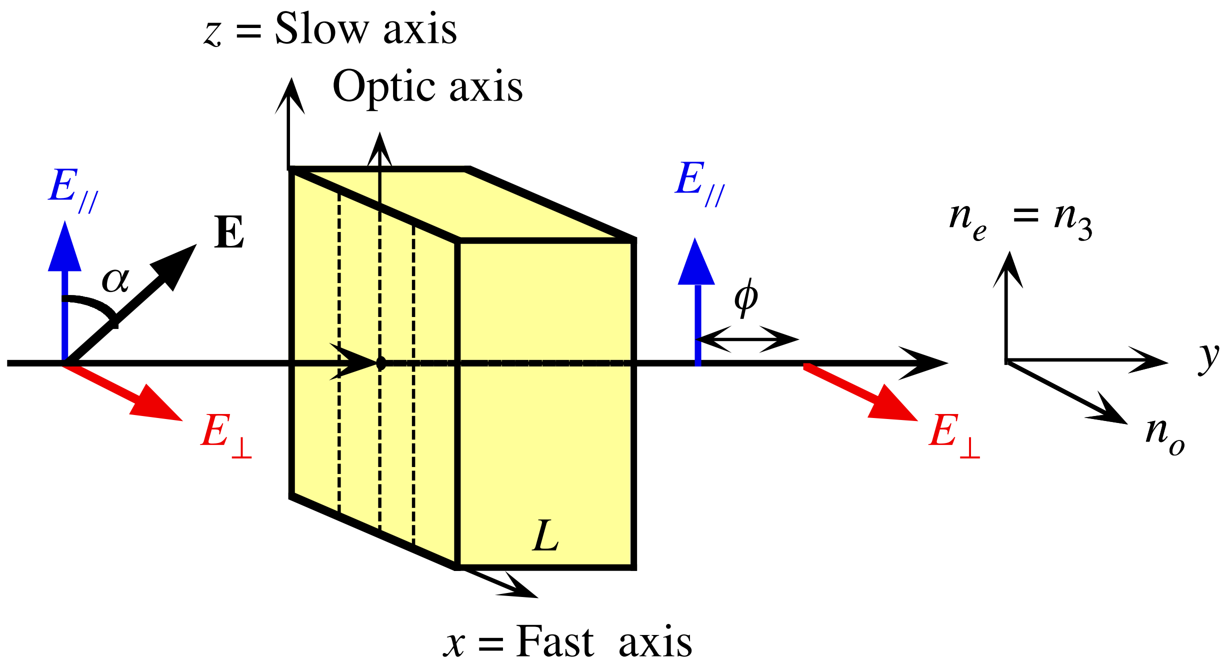
(a) Wavevector surface cuts in the *xz* plane for *o*- and *e*-waves. (b) An extraordinary wave in an anisotropic crystal with a $\mathbf{k}_e$ at an angle to the optic axis. The electric field is not normal to $\mathbf{k}_e$. The energy flow (group velocity) is along $\mathbf{S}_e$ which is different than $\mathbf{k}_e$.



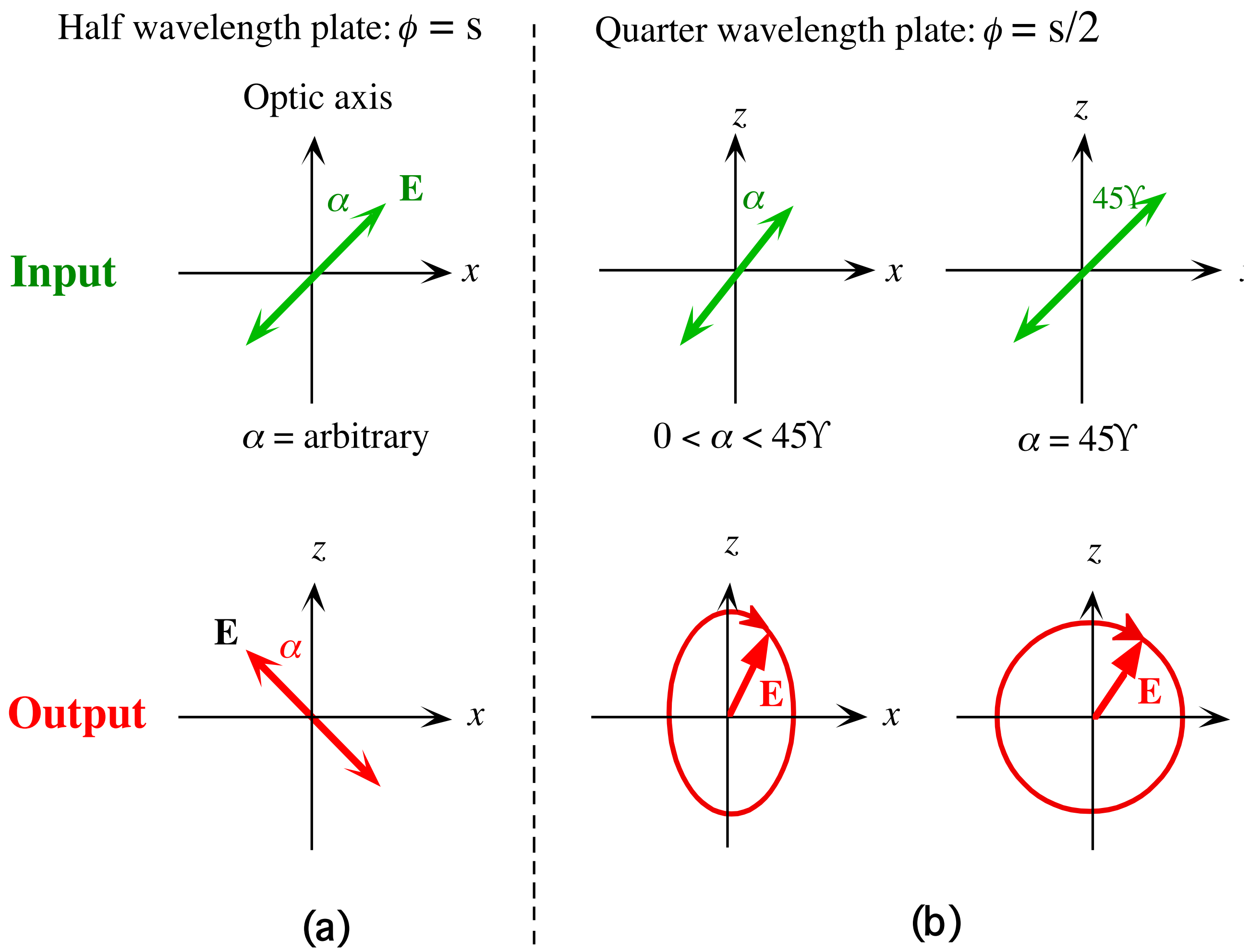
An EM wave that is off the optic axis of a calcite crystal splits into two waves called ordinary and extraordinary waves. These waves have orthogonal polarizations and travel with different velocities. The *o*-wave has a polarization that is always perpendicular to the optical axis.



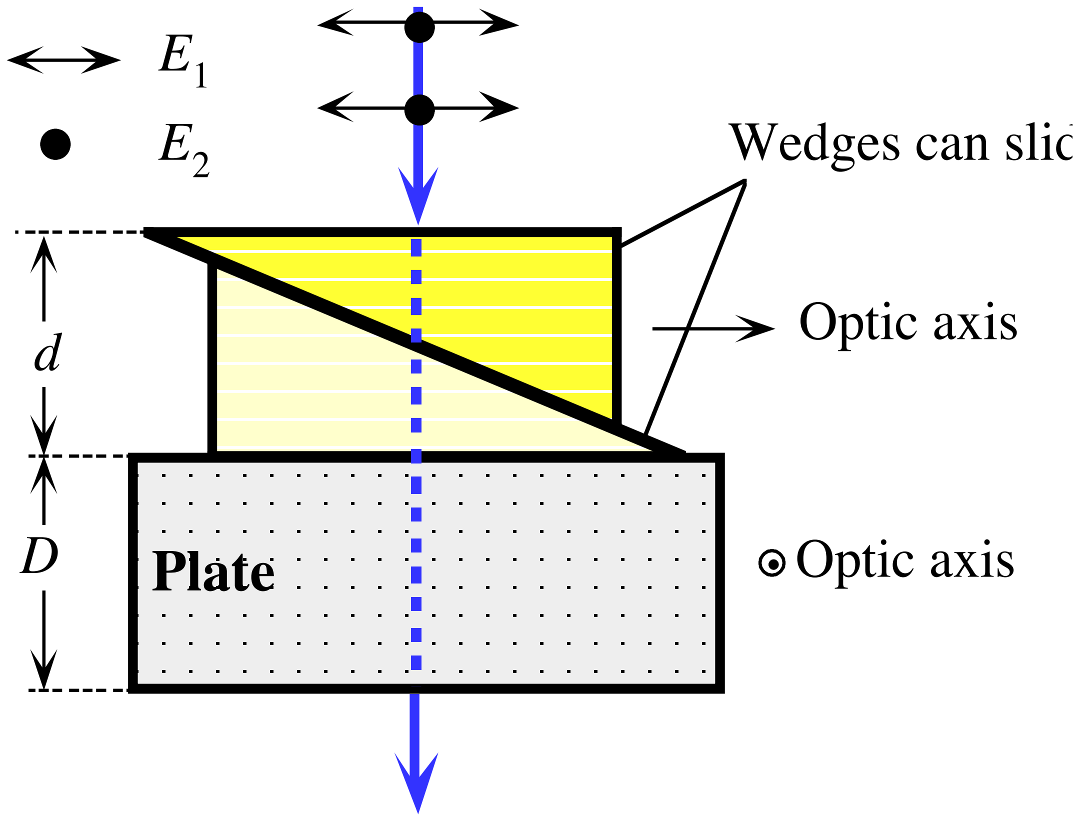
(a) A birefringent crystal plate with the optic axis parallel to the plate surfaces. (b) A birefringent crystal plate with the optic axis perpendicular to the plate surfaces.



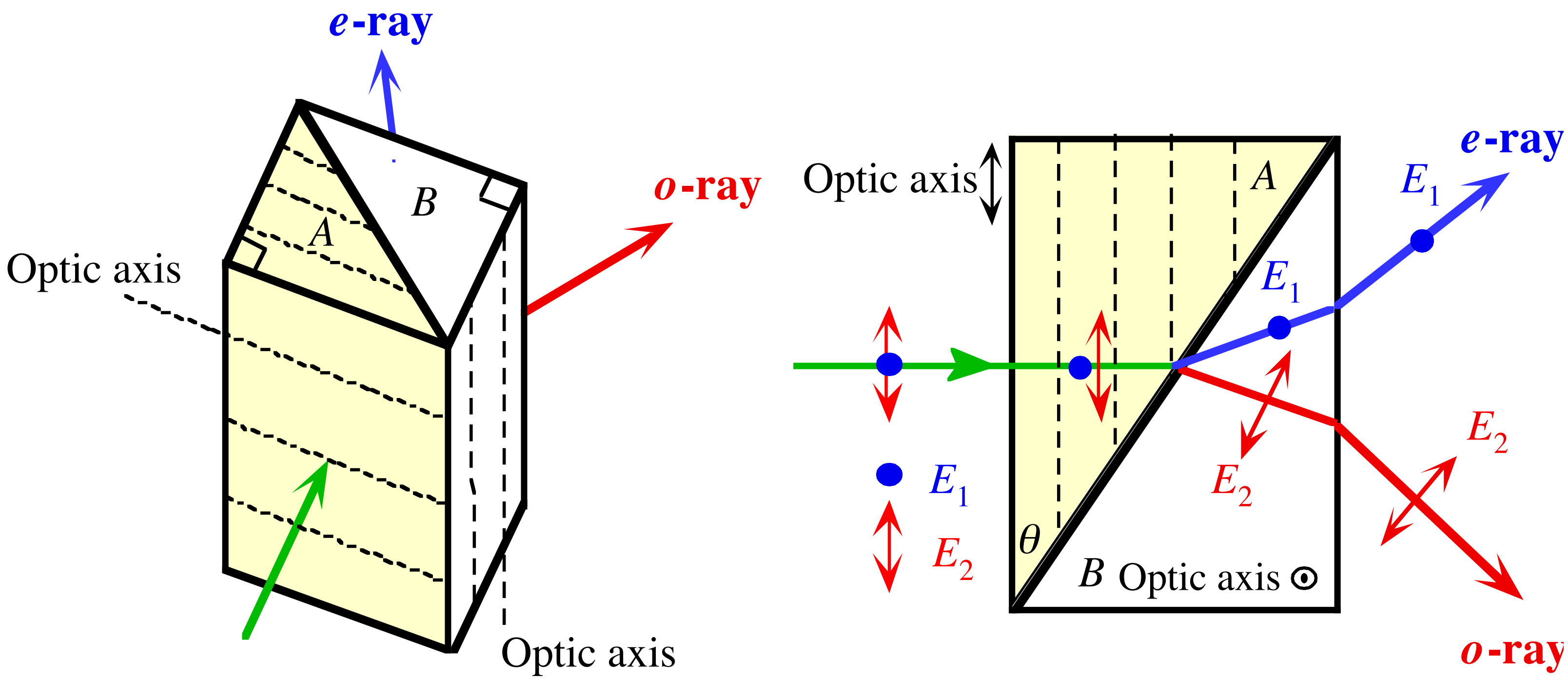
A retarder plate. The optic axis is parallel to the plate face. The *o*- and *e*-waves travel in the same direction but at different speeds.



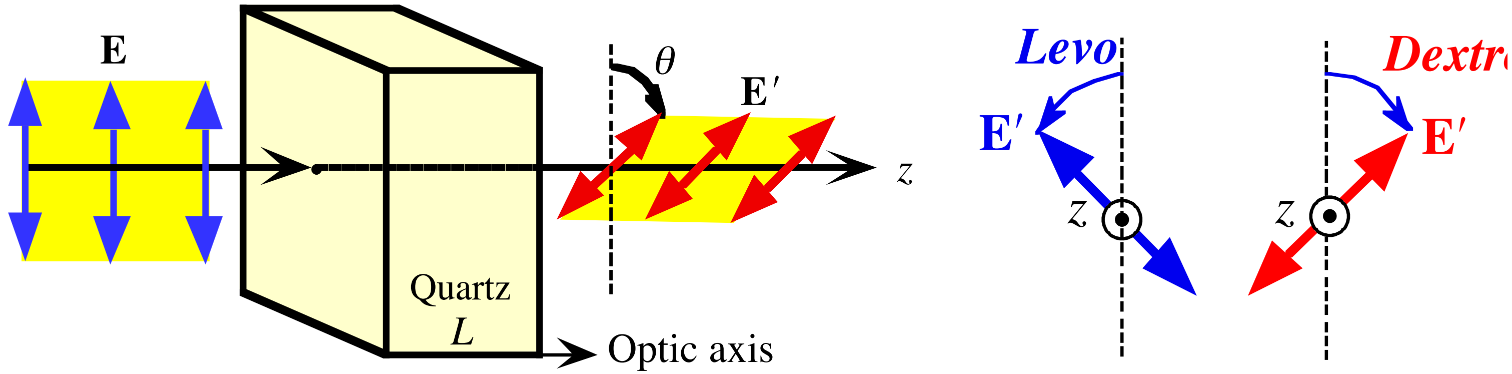
Input and output polarizations of light through (a) a half-wavelength plate and (b) through a quarter-wavelength plate.



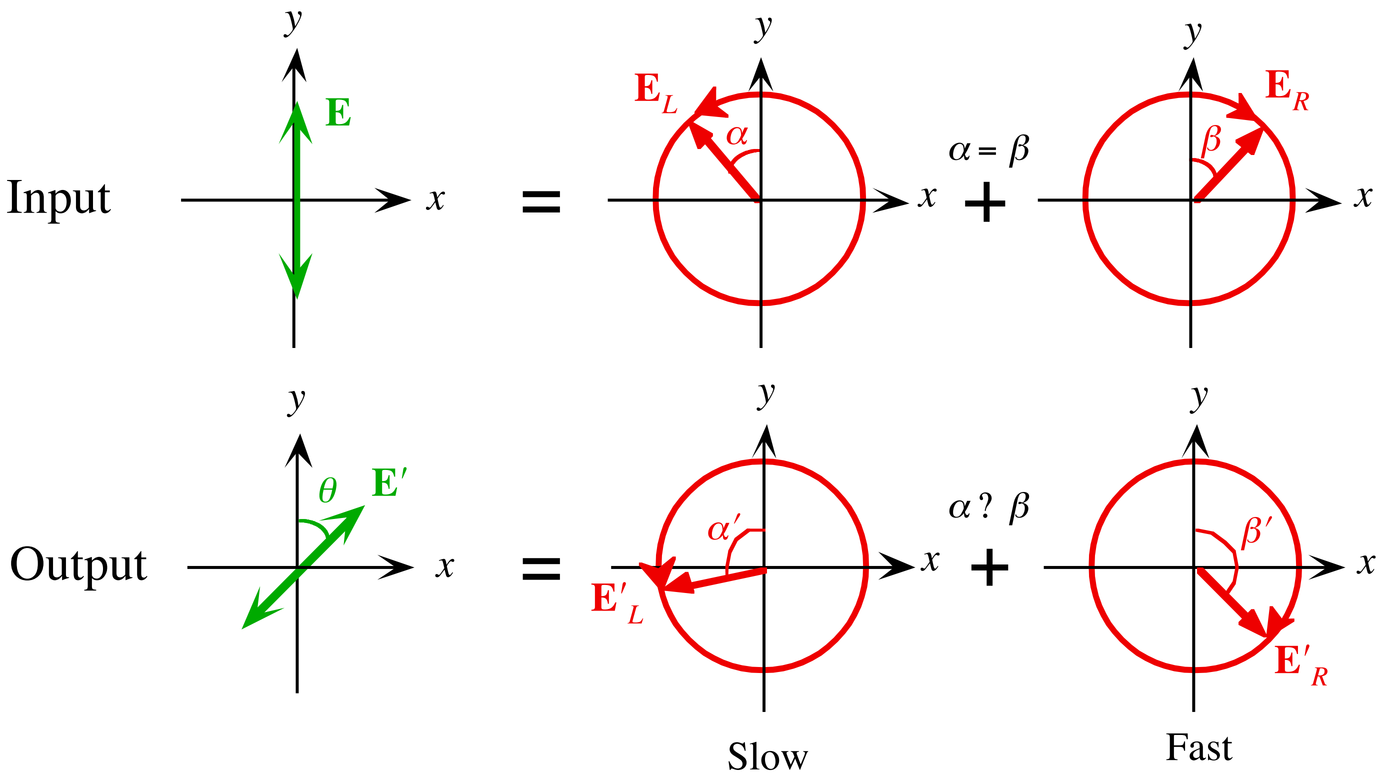
Soleil-Babinet Compensator



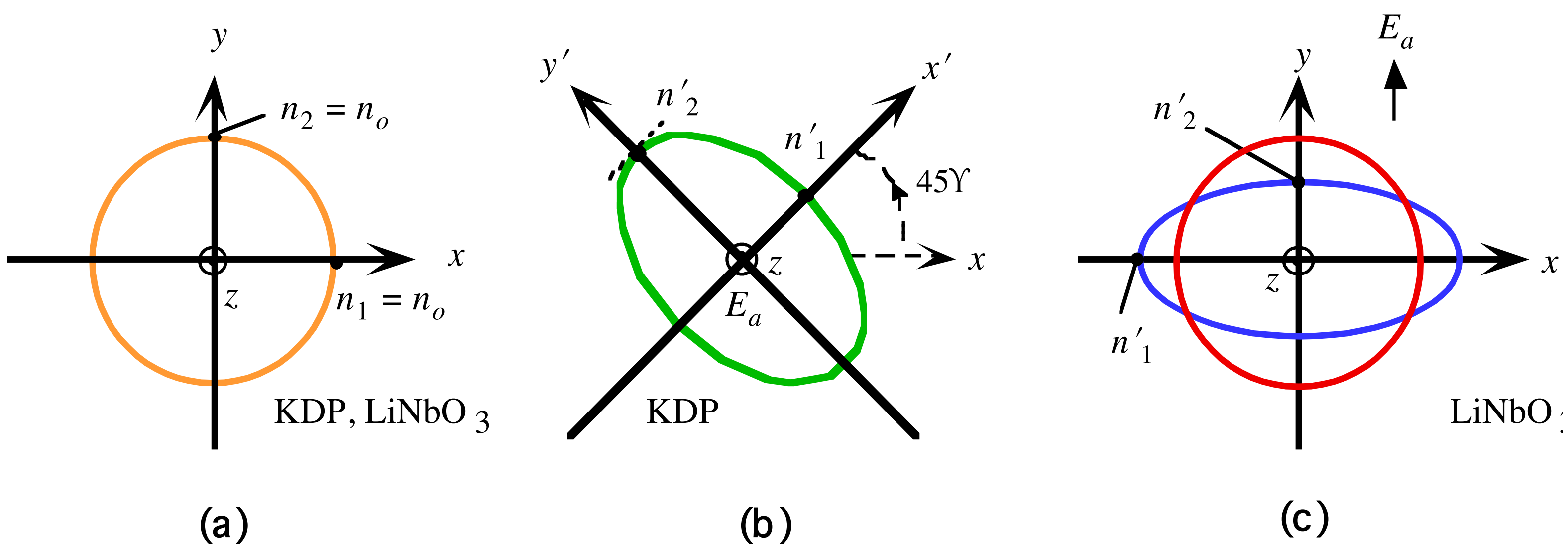
The Wollaston prism is a beam polarization splitter. E_1 is orthogonal to the plane of the paper and also to the optic axis of the first prism. E_2 is in the plane of the paper and orthogonal to E_1.



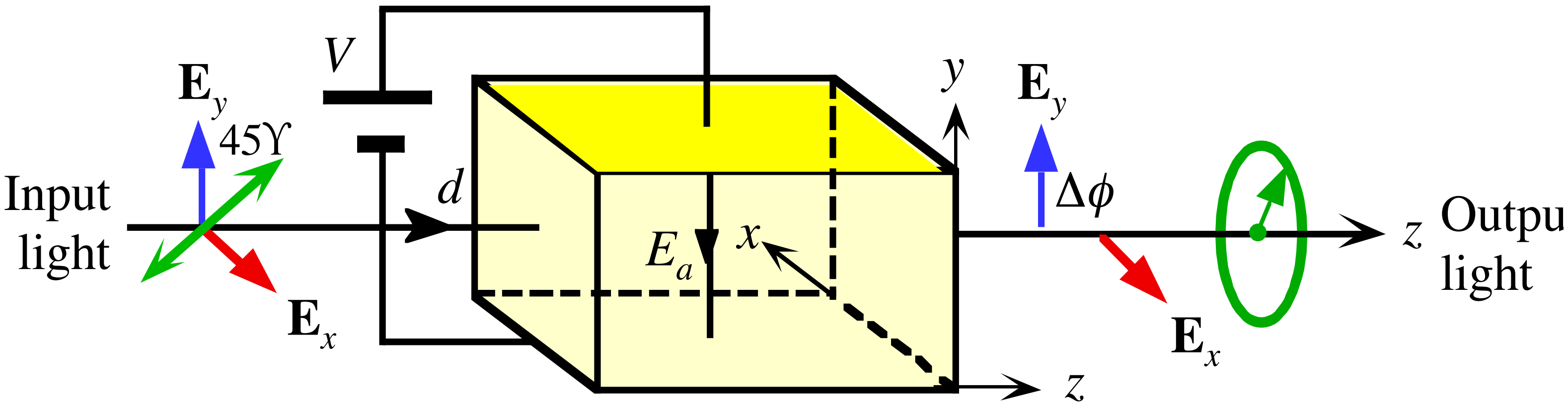
An optically active material such as quartz rotates the plane of polarization of the incident wave: The optical field **E** rotated to **E**′. If we reflect the wave back into the material, **E**′ rotates back to **E**.



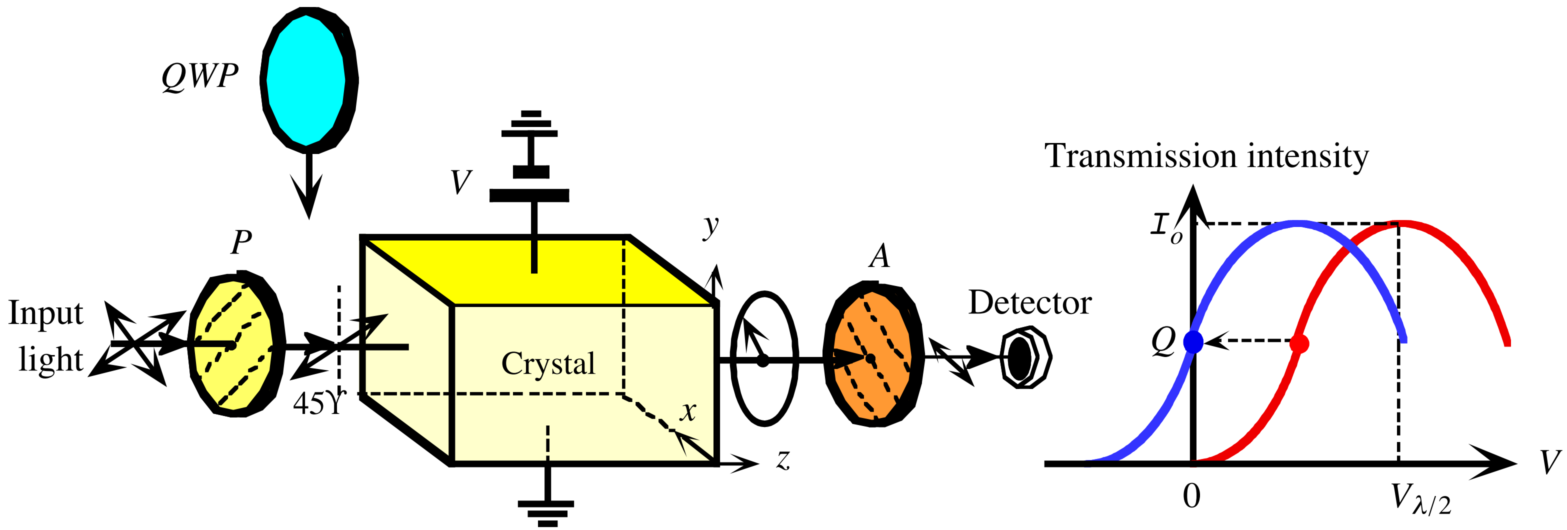
Vertically polarized wave at the input can be thought of as two right and left handed circularly polarized waves that are symmetrical, *i.e.* at any instant $\alpha = \beta$. If these travel at different velocities through a medium then at the output they are no longer symmetric with respect to y, α ? β., and the result is a vector $\mathbf{E}'$ at an angle θ to y.



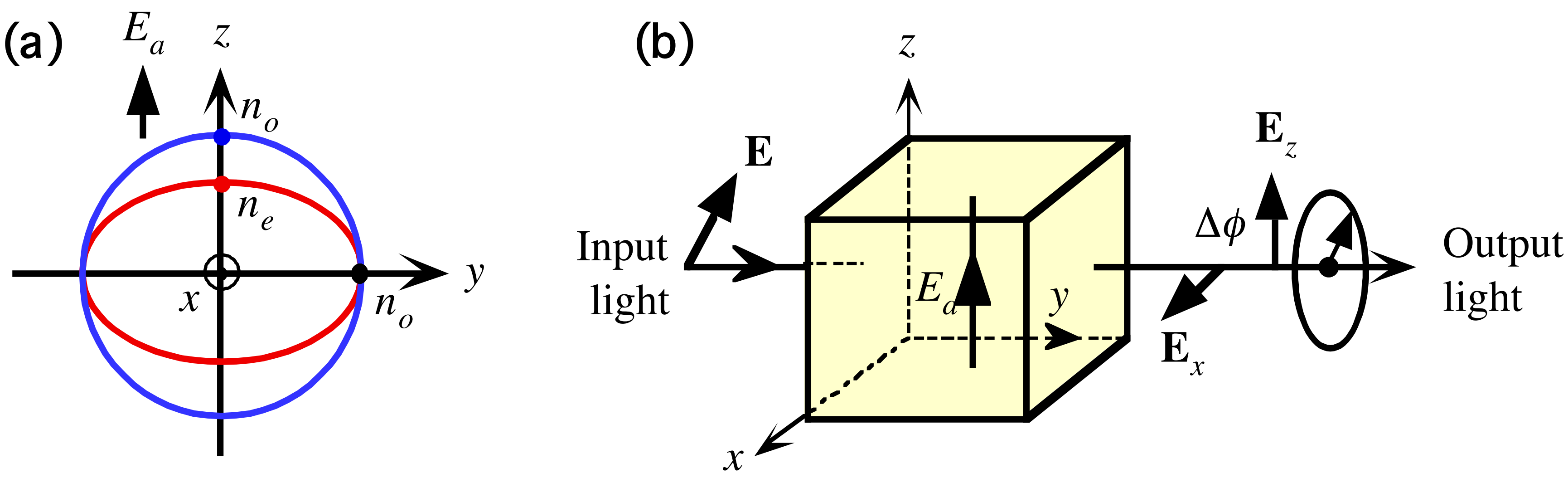
(a) Cross section of the optical indicatrix with no applied field, $n_1 = n_2 = n_o$ (b) Th applied external field modifies the optical indicatrix. In a KDP crystal, it rotates the principal axes by 45ϒto x' and y' and n_1 and n_2 change to n'_1 and n'_2. (c) Applied field along y in $LiNbO_2$ modifies the indicatrix and changes n_1 and n_2 change to n and n'_2.



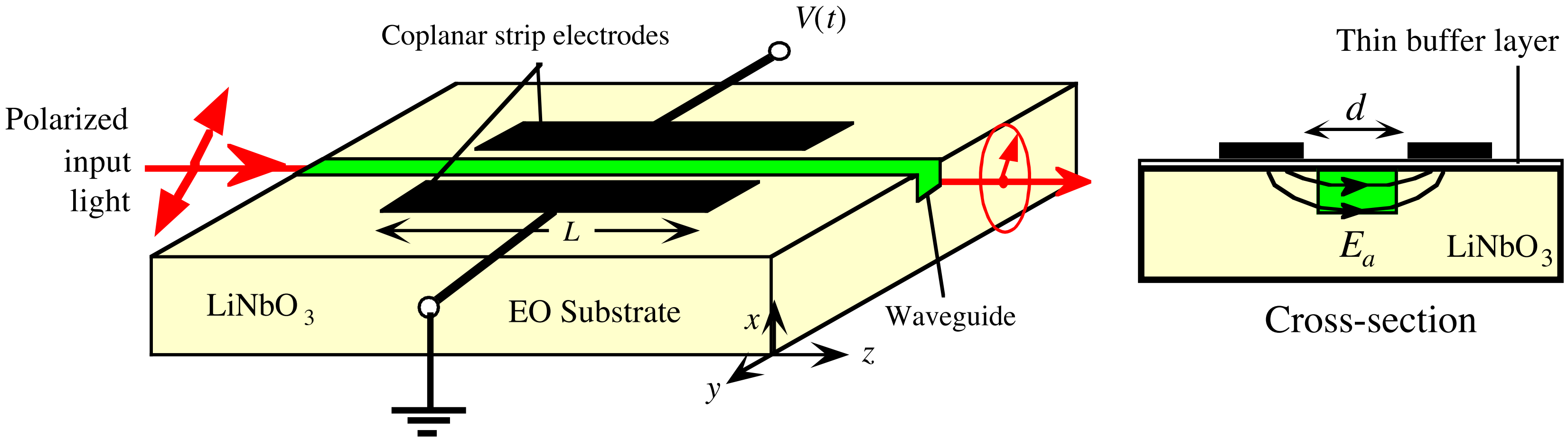
Tranverse Pockels cell phase modulator. A linearly polarized input light into an electro-optic crystal emerges as a circularly polarized light.



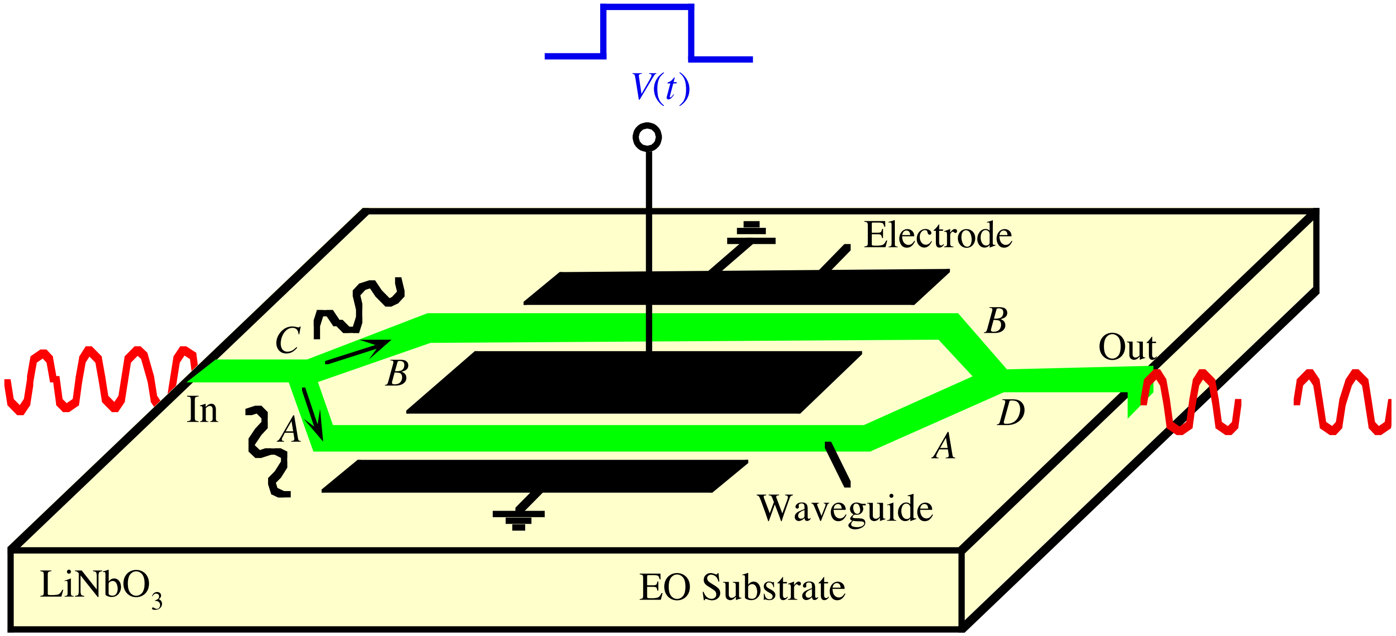
Left: A tranverse Pockels cell intensity modulator. The polarizer *P* and analyzer *A* have their transmission axis at right angles and *P* polarizes at an angle 45ϒto *y*-axis. Right: Transmission intensity vs. applied voltage characteristics. If a quarter-wave plate (*QWP*) is inserted after *P*, the characteristic is shifted to the dashed curve.



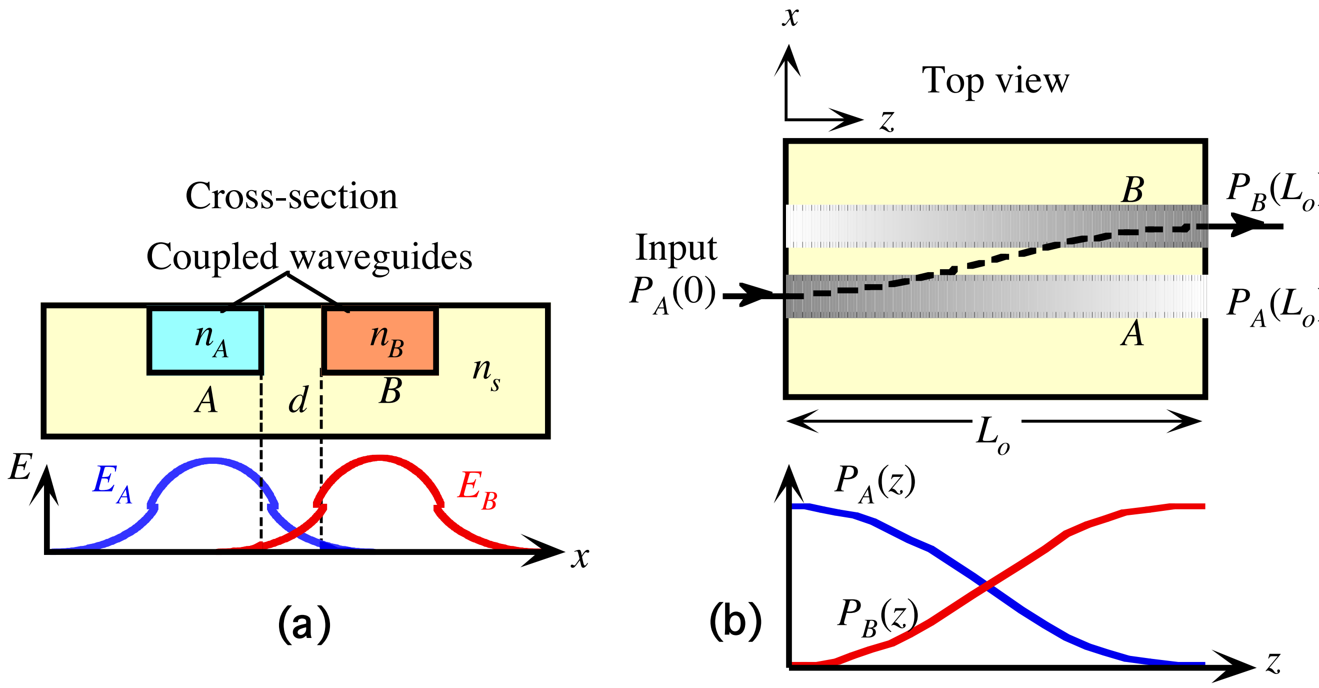
(a) An applied electric field, via the Kerr effect, induces birefringences in an otherwise optically istropic material. (b) A Kerr cell phase modulator.



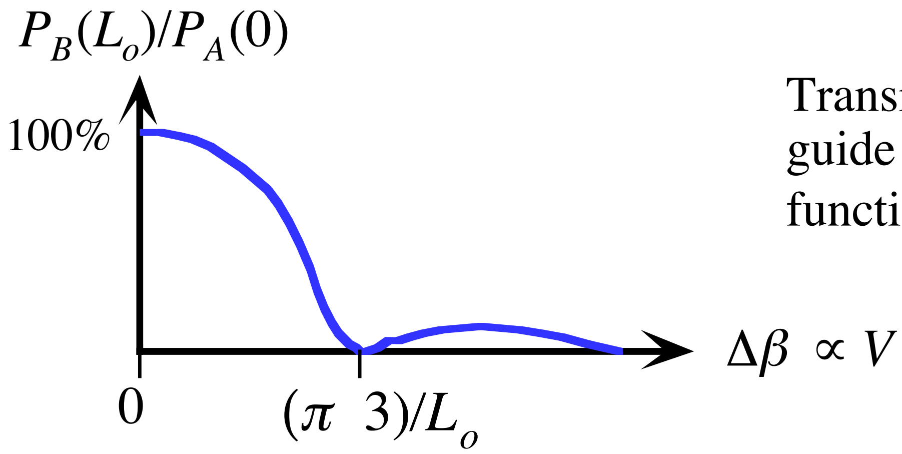
Integrated tranverse Pockels cell phase modulator in which a waveguide is diffused into an electro-optic (EO) substrate. Coplanar strip electrodes apply a transverse field E_a through the waveguide. The substrate is an x-cut $LiNbO_3$ and typically there is a thin dielectric buffer layer (*e.g.* ~200 nm thick SiO_2) between the surface electrodes and the substrate to separate the electrodes away from the waveguide.



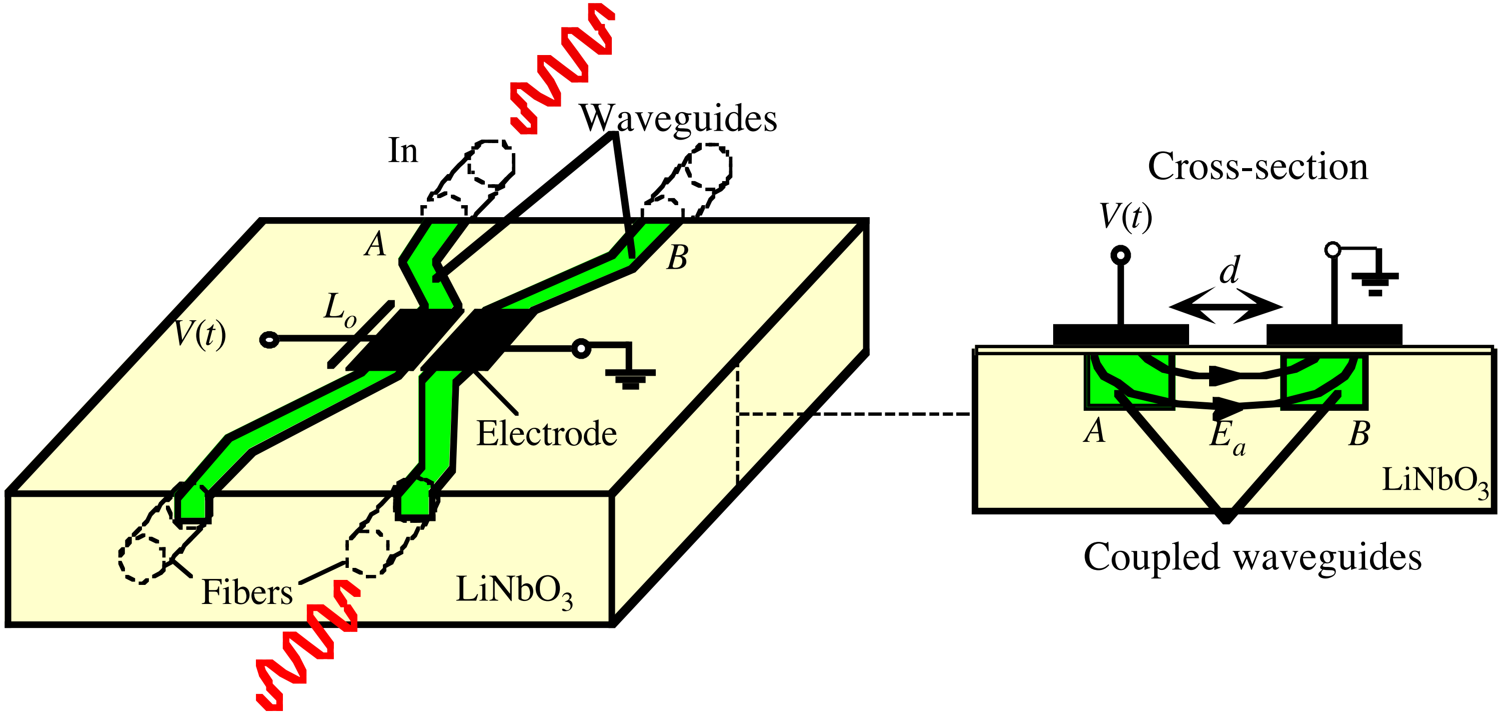
An integrated Mach-Zender optical intensity modulator. The input light is split into two coherent waves *A* and *B*, which are phase shifted by the applied voltage, and then the two are combined again at the output.



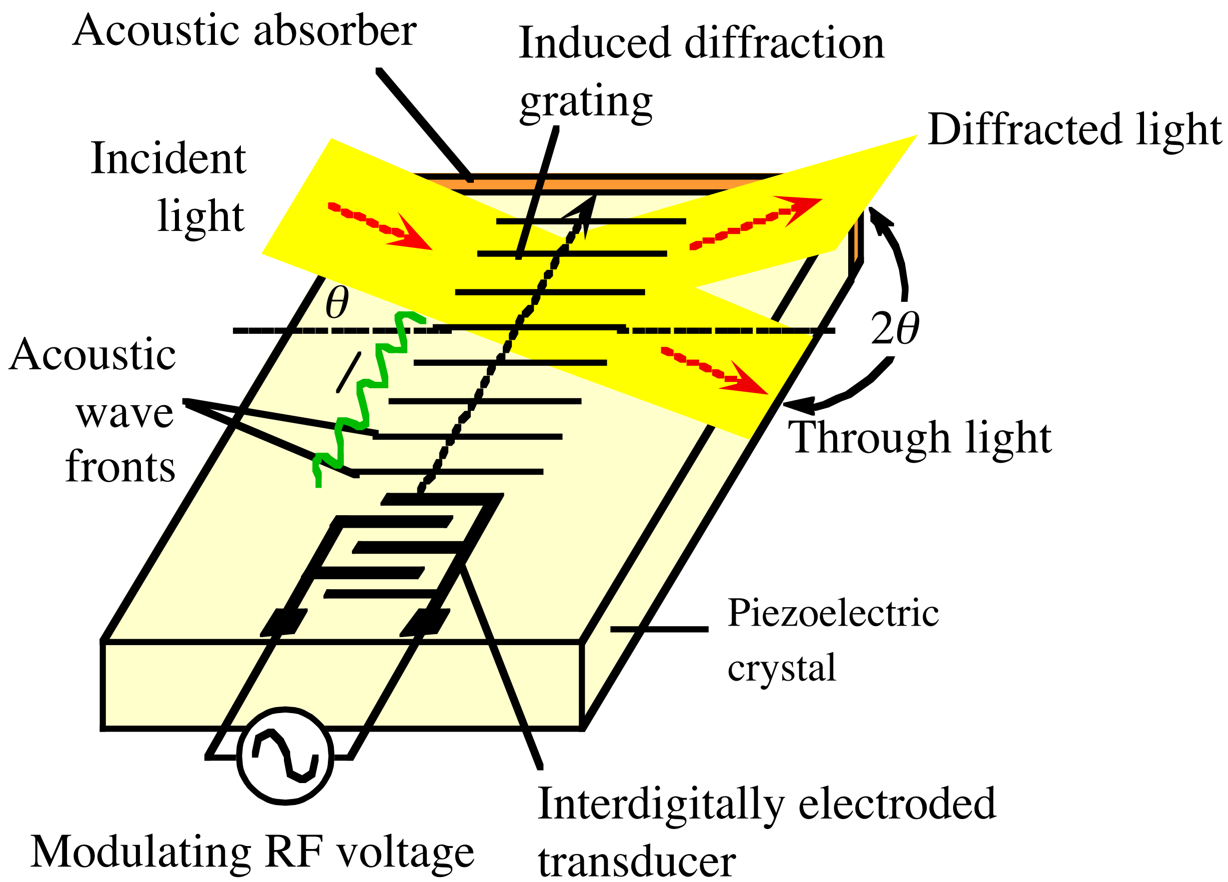
(a) Cross section of two closely spaced waveguides *A* and *B* (separated by *d*) embedded in a substrate. The evanescent field from *A* extends into *B* and vice versa Note: n_A and $n_B > n_s$ (= substrate index).
(b) Top view of the two guides *A* and *B* that are coupled along the *z*-direction. Light is fed into *A* at $z = 0$, and it is gradually transferred to *B* along *z*. At $z = L_o$, all the light been transferred to *B* . Beyond this point, light begins to be transferred back to *A* in the same way.



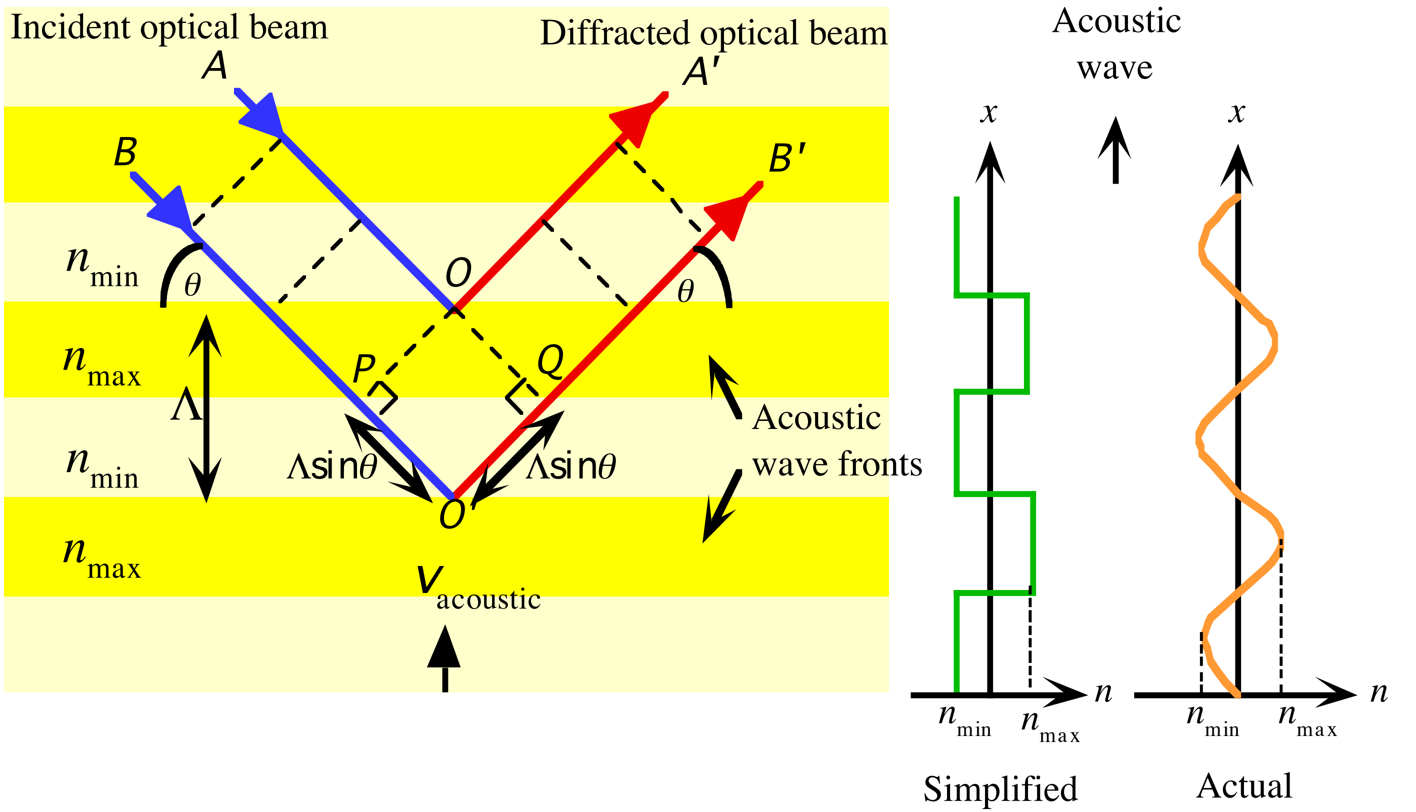
Transmission power ratio from guide *A* to guide *B* over the transmission length L_o as a function of mismatch $\Delta\beta$.



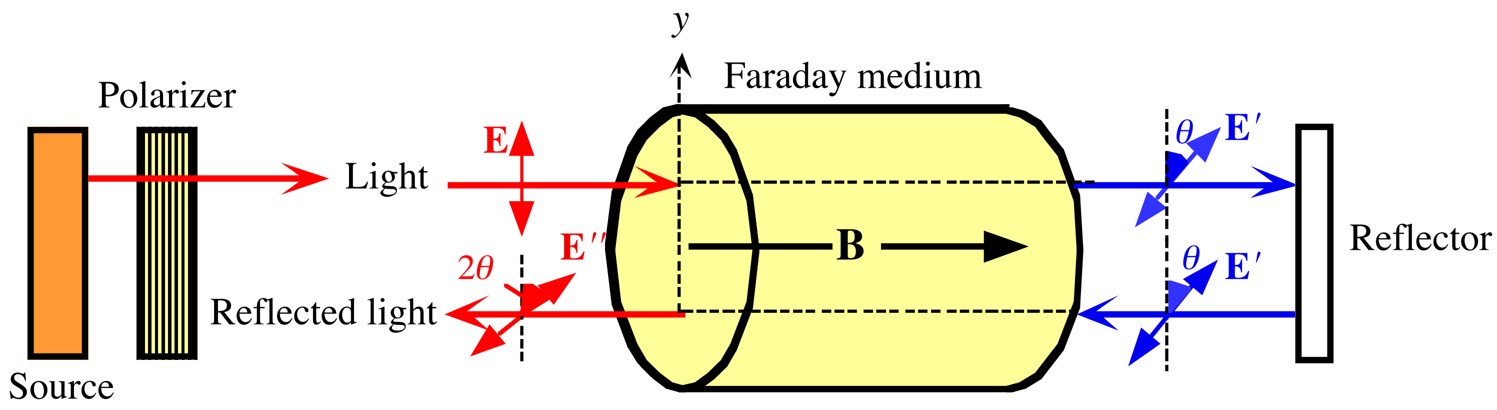
An integrated directional coupler. Applied field E_a alters the refractive indices of th
two guides and changes the strength of coupling.



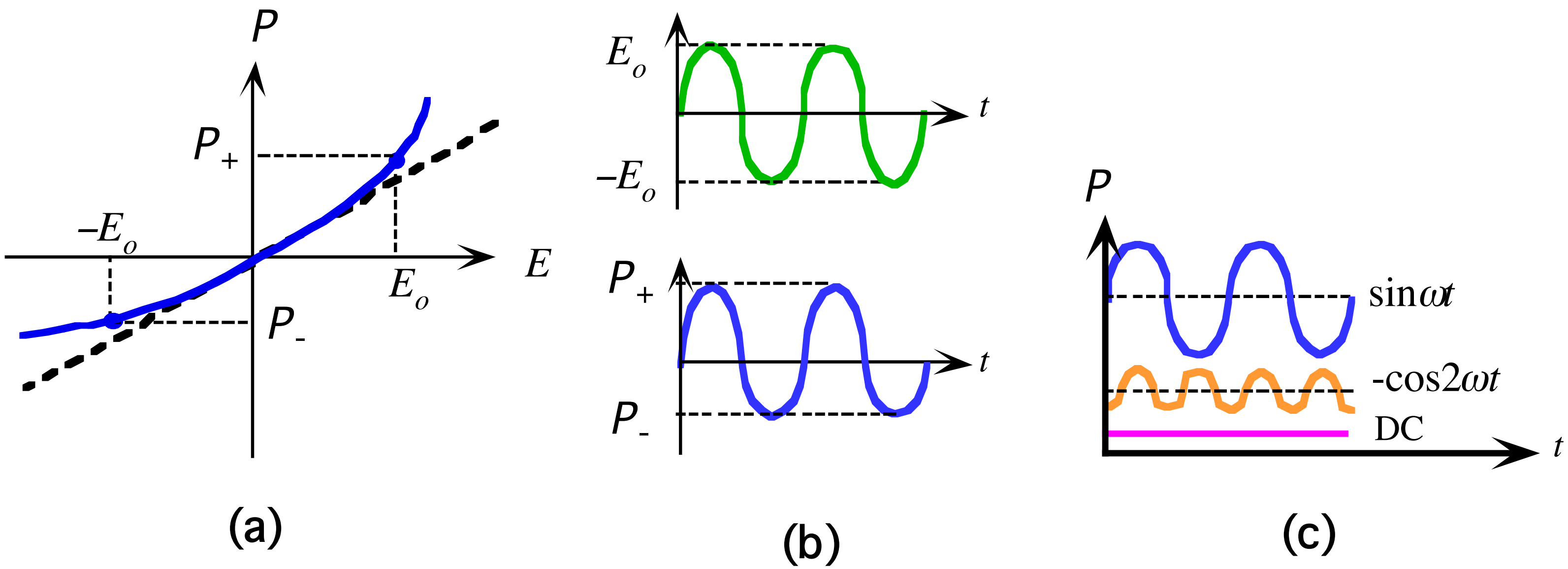
Traveling acoustic waves create a harmonic variation in the refractive index and thereby create a diffraction grating that diffracts the incident beam throug an angle 2θ.



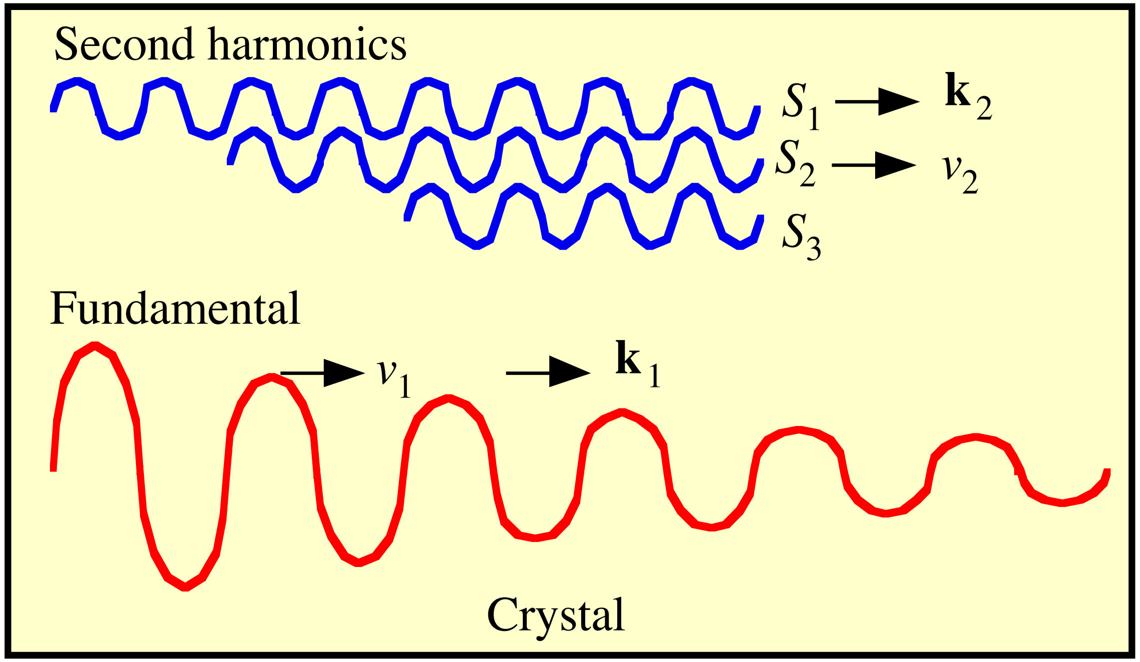
Consider two coherent optical waves A and B being "reflected" (strictly, scattered) from two adjacent acoustic wavefronts to become A' and B'. These reflected waves can only constitute the diffracted beam if they are in phase. The angle θ is exaggerated (typically this is a few degrees).



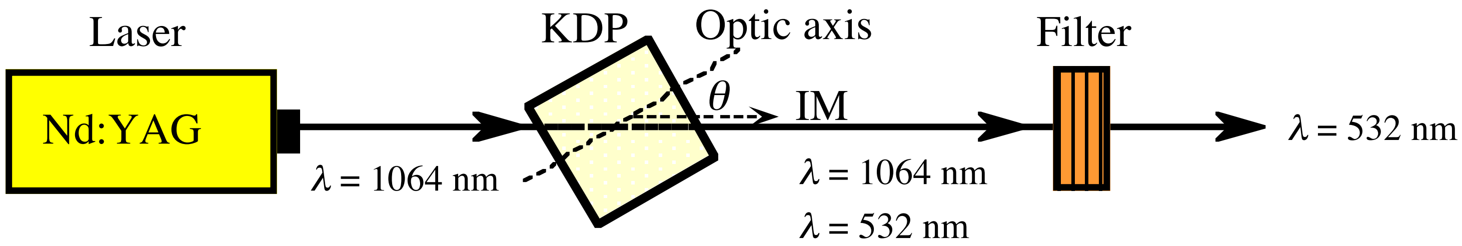
The sense of rotation of the optical field **E** depends only on the direction of the magnetic field for a given medium (given Verdet constant). If light is reflected back into the Faraday medium, the field rotates a further θ in the same sense to come out as $\mathbf{E}''$ with a 2θ rotation with respect to **E**.



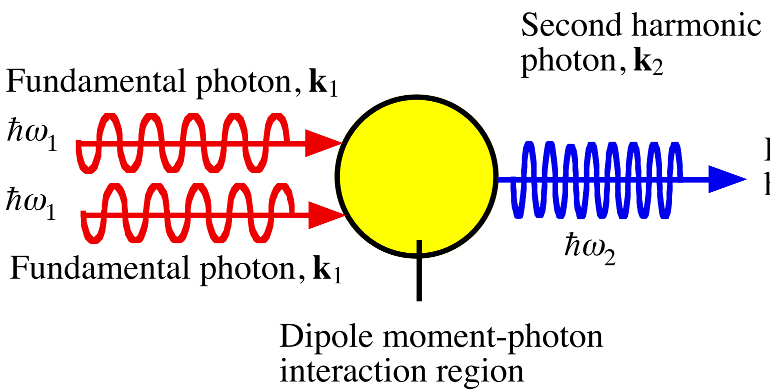
(a) Induced polarization vs. optical field for a nonlinear medium. (b) Sinusoidal optical field oscillations between $\pm E_o$ result in polarization oscillations between P_+ and P_-. (c) The polarization oscillation can be represented by sinusoidal oscillations at angular frequencies ω (fundamental), 2ω (second harmonic) and a small DC component.



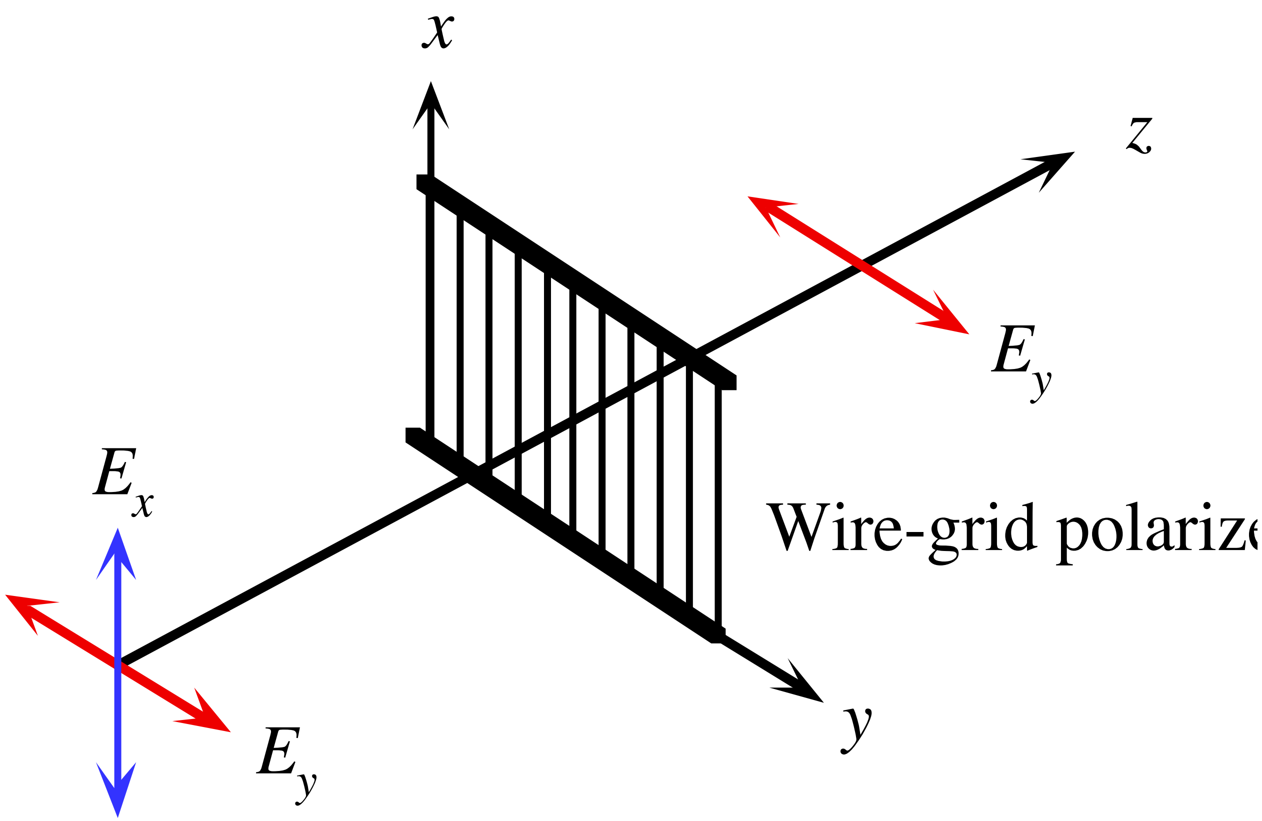
As the fundamental wave propagates, it periodically generates second harmonic waves (S_1, S_2, S_3, ...) and if these are in phase then the amplitude of the second harmonic light builds up.



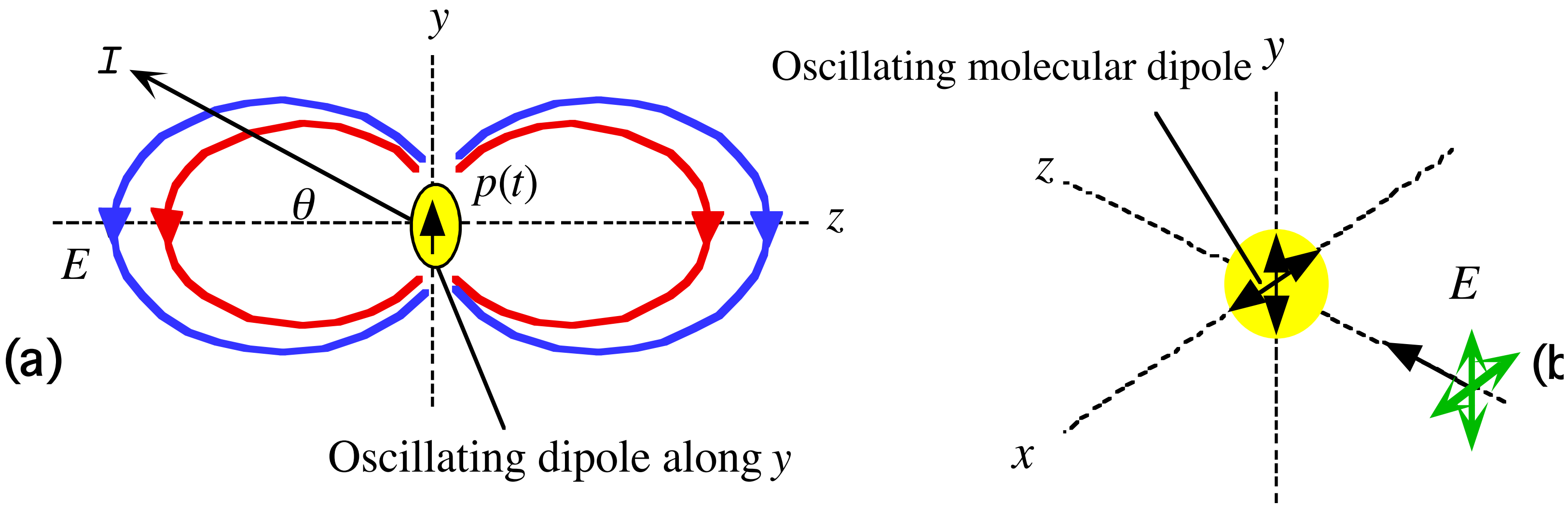
A simplified schematic illustration of optical frequency doubling using a KDP (potassium dihydrogen phosphate) crystal. IM is the index matched direction at ar angle θ (about 35Ÿ) to the optic axis along which $n_e(2\omega) = n_o(\omega)$. The focusing o the laser beam onto the KDP crystal and the collimation of the light emerging from the crystal are not shown.



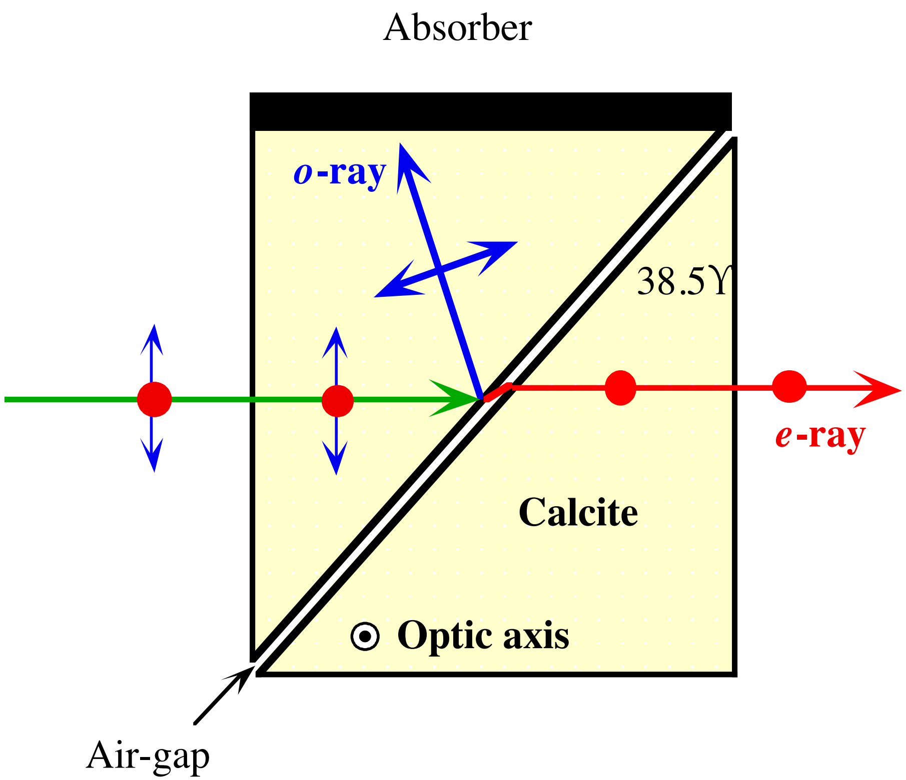
Photonic interpretation of second harmonic generation (SHG)



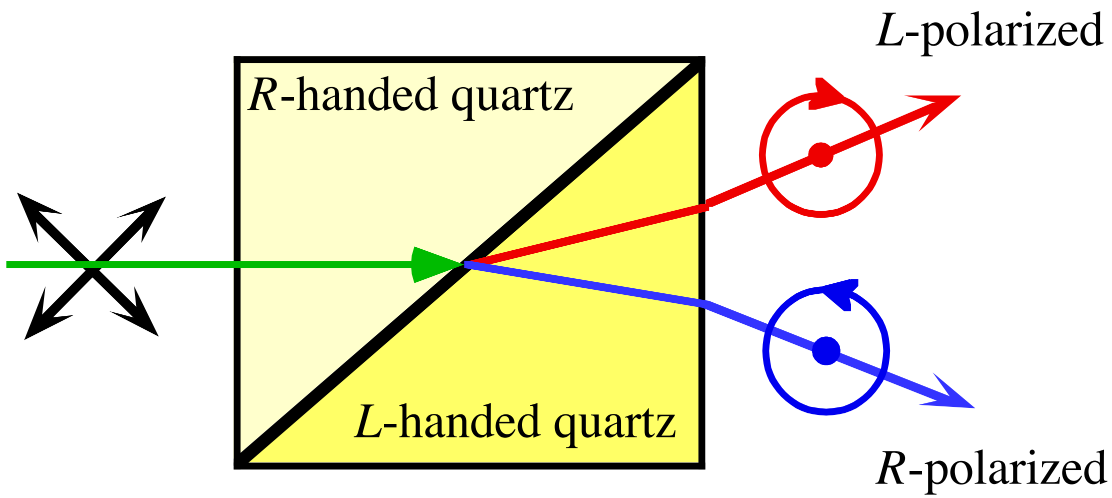
The wire grid-acts as a polarizer



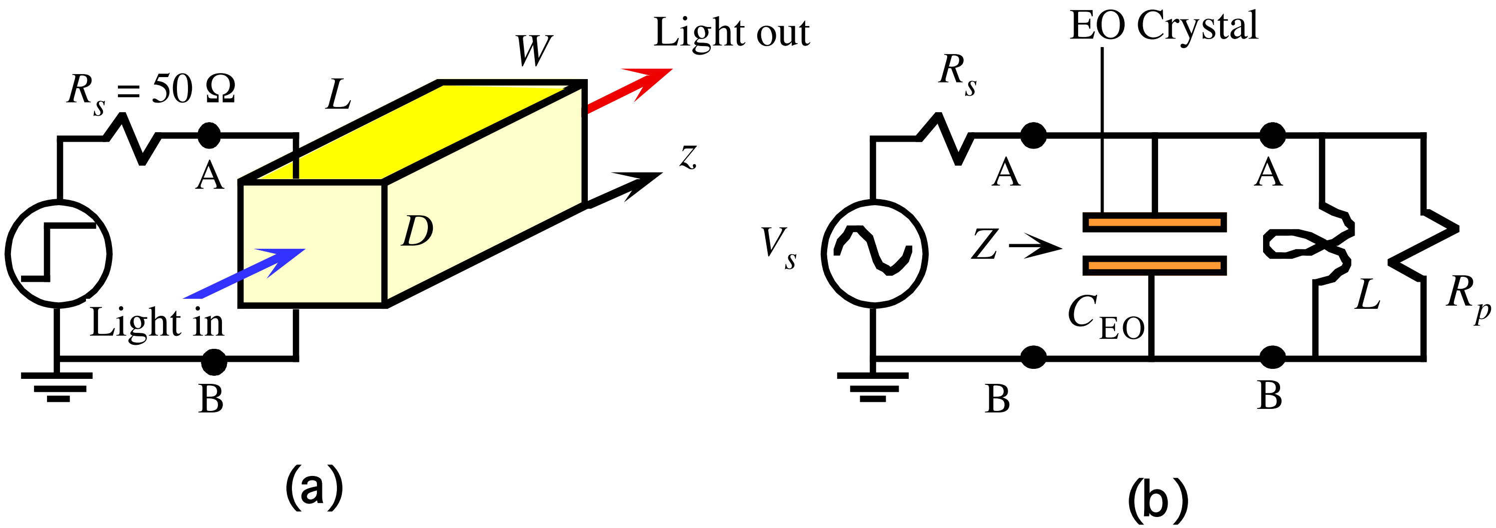
(a) A snap shot of the field pattern around an oscillating dipole moment in the *y*-direction. Maximum electromagnetic radiation is perpendicular to the dipole axis and there is no radiation along the dipole axis. (b) Scattering of electromagnetic waves from induced molecular dipole oscillations is anisotropic.



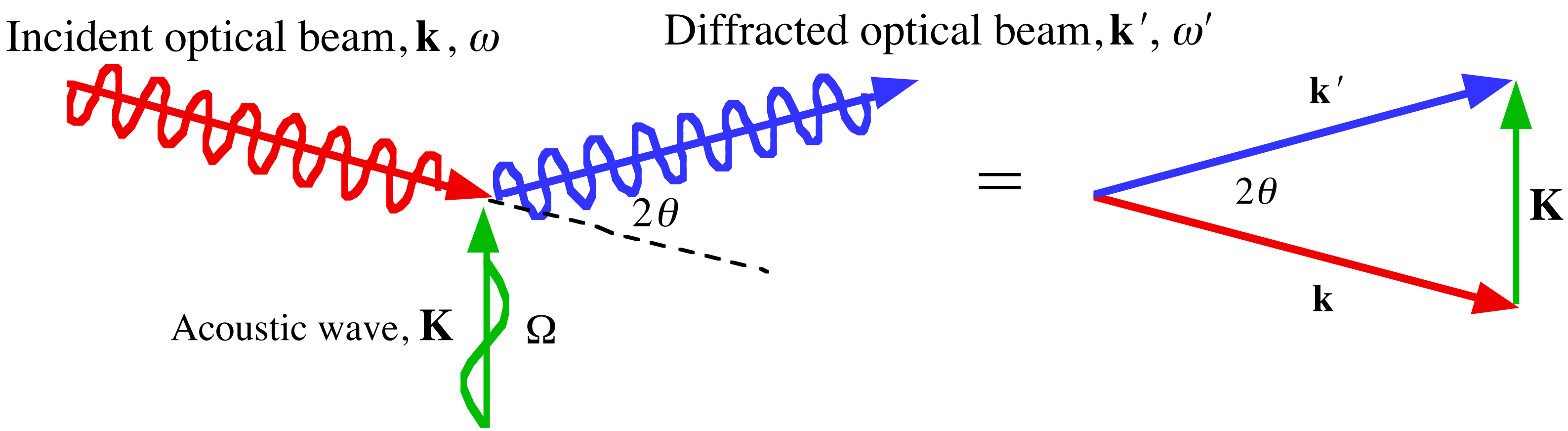
The Glan-Foucault prism provides linearly polarized light



The Fresnel prism for separating unpolarized light into two divergent beams with opposite circular polarizations (*R* = right, *L* = left; divergence is exaggerated)



(a) A step voltage is suddenly applied to an EO modulator. (b) An inductance L with an equivalent parallel resistance R_p is placed across the EO crystal modulator to match the capacitance C_{EO}.



Wavevectors for the incident and diffracted optical waves and the acoustic wave.