Integrated optics

(Selected topics)

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Lecture plan:

1. Materials for integrated optics
2. Something from Crystal optics
3. Electrooptical effect (Pockels, Kerr's effect)
4. Photorefractive effect
5. Applications

1. Materials for integrated optics

a) Structure:

- Crystalline materials (Al_2O_3, Y_2O_3, Ta_2O_5, TiO_2, $LiNbO_3$, $LiTaO_3$, $BaTiO_3$, GaAs, ZnS, CdS…)
- Amorphous materials (silica glass, doped glass)
- Ceramics
- Liquid crystals

b) Aplications:

- Passive (fibers and other guiding structures)
- Active (for linear and nonlinear active structures)

Requirements:

Materials - optical characteristics

1. Attenuation (below 1 dB/cm in waveguide)
2. Refractive index value (waveguide, coating)
3. Spectral transmission characteristics
4. Technological feasibility. Compatibility of opto and microelectronics technologies.
5. Properties enabling monolithic device integration (passive and active devices build on the same substrate)
6. Stability of properties (optical homogeneity, mechanical properties, thermal resistance …)
7. Resistance to high beam intensities
8. Mass production capability

Example:

Materials for optical waveguides

Glasses

• silica SiO_2

• sodium free glasses C-7025

• soda lime glass

• halide glasses

• chalcogenide glasses (e.g. As_2S_3)

• halide glasses (e.g. ZBLAN - ZrF_4, BaF_2, LaF_3, AlF_3,)

Oxides and nitrides ZnO, Ta_2O_5, Nb_2O_5, TiO_2, Si_3N_4

Dielectric crystals $LiNbO_3$, $LiTaO_3$

Ferromagnetic crystals YIG ($Y_3Fe_5O_{12}$) optical isolators

Semiconductors GaAs, AlGaAs, InGaAs, InGaAsP, silicon (λ > 1000nm, ASOC = active silicon integrated optic circuits)

Polymers: PMMA, PS, polyamides, epoxy resins

Materials - photonic light sources

Semiconductors

GaAs, AlGaAs, InGaAsP, InAsGa

Crystals (doped crystals)

$Cr:Al_2O_3$, Nd:YAG, $Er:LiNbO_3$

Doped glasses

$Er:SiO_2$ (EDFA), Pd:ZBLAN (PDFFA)

Liquids (dyes)

Gases (He-Ne mixture, Ar+, N, CO_2)

2. Crystal optics

Classification of solids

The elements and their compounds which aggregate into the solid state can be classified as amorphous, polycrystalline, or single-crystalline materials.

The distinction among these three classes of solids depends on the arrangement of atoms in the material.

When the atoms in the material are arranged in a regular manner with a three-dimensional periodicity that extends throughout a given volume of the solid, the material is considered to be a single crystal.

In polycrystalline materials the periodic arrangement of atoms is interrupted randomly along two-dimensional sections that can intersect, dividing a given volume of solid into a number of smaller single –crystalline regions or grains.

If there is no periodicity in the arrangement of atoms, the material is classified as amorphous.

Physical properties of crystals

- in consequence of the crystal structure, the ideal crystal is a homogeneous and anisotropic medium
- a great number of physical effects in solids can be described by a linear tensor-type relation

$$\boldsymbol{M} = \boldsymbol{T} \cdot \boldsymbol{N}$$

$\boldsymbol{M}$, $\boldsymbol{N}$ – represent any physical fields, $\boldsymbol{T}$ – describes the physical property

- symmetry of the physical property manifests oneself in symmetry of the tensor
- consider the symmetric tensor of the second order $\boldsymbol{T}_{ij,}$ where

$$\sum_{ij} \boldsymbol{T}_{ij}\, x_i\, x_j = \pm 1$$

$$(T_{11} x_1^2 + T_{22} x_2^2 + T_{33} x_3^2 + 2T_{23} x_2 x_3 + 2T_{31} x_3 x_1 + 2T_{12} x_1 x_2 = \pm 1)$$

is the equation of its characteristic surface (indicatrix)

- after a proper transformation we get the diagonal form

$$T'_{11} x_1'^2 + T'_{22} x_2'^2 + T'_{33} x_3'^2 = \pm 1$$

which is helpful for determining the shape and symmetry of the characteristic surface

- there are three possible types of symmetry

  a) if $T_{11} \neq T_{22} \neq T_{33}$, the symmetry is mmm and the indicatrix is the general ellipsoid, hyperboloid and elliptical or hyperbolic cylinder,

  b) if $T_{11} = T_{22} \neq T_{33}$, the symmetry is $\infty/mm, \quad \infty \,||\, x_3$

     $T_{33} = T_{11} \neq T_{22}$, the symmetry is $\infty/m\,m, \quad \infty \,||\, x_2$

     $T_{22} = T_{33} \neq T_{11}$, the symmetry is $\infty/m\,m, \quad \infty \,||\, x_1$

     and the indicatrix is the cylindrical ellipsoid, cylinder or the pair of the parallel planes,

  c) if $T_{11} = T_{22} = T_{33}$, the symmetry is $\infty\infty m$ and the indicatrix is the sphere

- the key physical property of optics is the electric permitivity represented by tensor $\boldsymbol{\varepsilon}_{ij}$ and indikatrix

$$\frac{x_1^2}{\varepsilon_{11}} + \frac{x_2^2}{\varepsilon_{22}} + \frac{x_3^2}{\varepsilon_{33}} = \frac{1}{e_0}$$

- in accordance with three types of symmetry mentioned above, there are only three types of characteristic surfaces

  a) <u>triaxial ellipsoid</u> – optically biaxial crystals (orthorhombic, monoclinic and triclinic crystals),

  b) <u>cylindrical ellipsoid with one optical axis</u> – optically uniaxial crystals (hexagonal, trigonal a tetragonal crystals),

  c) <u>sphere</u> – the every direction is the optical axis –optically isotropic matters (cubic crystals)

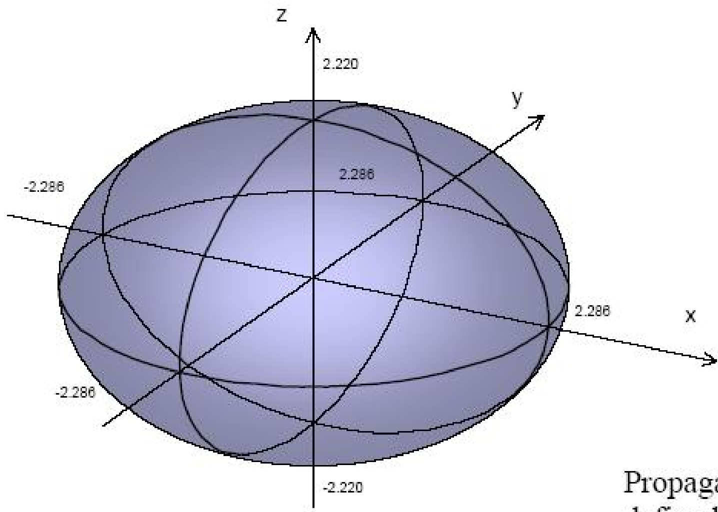


Fig. 1 *Optical indikatrix of $LiNbO_3$*

Propagation conditions are defined through:

- propagation direction
- polarization
- crystallographic orientation

<u>The plane wave propagation in uniaxial crystals</u>

Maxwell's equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{D} = \rho \qquad \nabla \cdot \vec{B} = 0$$

Constitutive equations, they describe the medium

$$\vec{D} = \bar{\bar{\varepsilon}}\vec{E} = \varepsilon_0 \vec{E} + \vec{P}$$

$$\vec{B} = \overline{\mu}\vec{H} = \mu_0 \vec{H} + \vec{M}$$

By definition

$$\mu_0 = 4\pi \cdot 10^{-7} N \cdot A^{-2}$$

$$\varepsilon_0 \cdot \mu_0 = c^{-2}$$

Permittivity and refractive index $\overline{\varepsilon} = \overline{n}^{2}$

It follows from Maxwell’s equations the relationship between $\vec{D}$ and $\vec{E}$

$$\vec{D} = \frac{k_0^2}{w_0^2 \cdot m_0} \cdot \left[\vec{E} - \left(\vec{a}_k \cdot \vec{E}\right) \cdot \vec{a}_k\right]$$

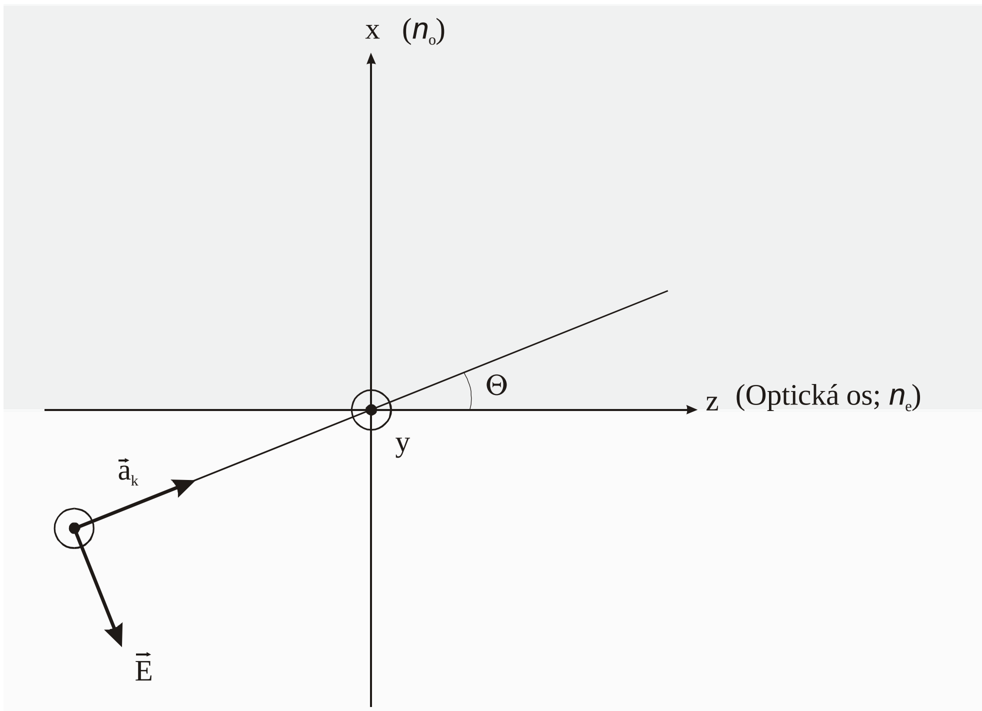


***Fig. 2** The plane wave propagation in uniaxial crystal*

The refractive index of the wave propagating across the medium

$$n_{eff} = \frac{n_o \cdot n_e}{\sqrt{n_0^2 \cdot \sin(\Theta) + n_e^2 \cdot \cos(\Theta)}}$$

3. Electrooptical effect

$$\vec{D} = e_0 \cdot \vec{E} + \vec{P}$$

$$\vec{P} = \vec{P}_0 + e_0 \cdot \overline{\overline{\boldsymbol{\chi}}} \cdot \vec{E} + e_0 \cdot \overline{\overline{\overline{\boldsymbol{\chi}}}} \cdot \vec{E} \cdot \vec{E} + e_0 \cdot \overline{\overline{\overline{\overline{\boldsymbol{\chi}}}}} \cdot \vec{E} \cdot \vec{E} \cdot \vec{E} + \mathbf{K}\ .$$

$\vec{P}_0 = 0$

$$D_i = \boldsymbol{\varepsilon}^0_{ij} \cdot E_j + \boldsymbol{\alpha}_{ijk} \cdot E_j \cdot E_k + \boldsymbol{\beta}_{ijkm} \cdot E_j \cdot E_k \cdot E_m + \mathbf{K},$$

$\boldsymbol{\varepsilon}^0_{ij} = e_0 \cdot \left(\delta_{ij} + \overline{\overline{\boldsymbol{\chi}}}\right)$, $\boldsymbol{\alpha}_{ijk} = e_0 \cdot \boldsymbol{\chi}_{ijk}$, $\boldsymbol{\beta}_{ijkm} = e_0 \cdot \boldsymbol{\chi}_{ijkm}$

$$\boldsymbol{\varepsilon}_{ij} = \frac{\partial D_i}{\partial E_j}$$

$$\boldsymbol{\varepsilon}_{ij} = \boldsymbol{\varepsilon}^{0}_{ij} + \boldsymbol{\alpha}'_{ijk} \cdot E_k + \boldsymbol{\beta}'_{ijkm} \cdot E_k \cdot E_m + \mathbf{K}\ .$$

$n^2_{ij} = \varepsilon_{ij}$

$$n^2_{ij} = \left(n^0 \cdot n^0\right)_{ij} + \boldsymbol{\alpha}''_{ijk} \cdot E_k + \boldsymbol{\beta}''_{ijkm} \cdot E_k \cdot E_m + \mathbf{K}\ ,$$

$$\Delta n^2_{ij} = \boldsymbol{\alpha}''_{ijk} \cdot E_k + \boldsymbol{\beta}''_{ijkm} \cdot E_k \cdot E_m$$

Let the $\boldsymbol{B}_{ij}$ be the tensor with diagonal components $d_{ij} \dfrac{e_0}{\boldsymbol{\varepsilon}_i}$, d_{ij} being Kronecker delta

$$\Delta \boldsymbol{B}_{ij} = \boldsymbol{r}_{ijk} \cdot E_k + \boldsymbol{s}_{ijkm} \cdot E_k \cdot E_m$$

$$\boldsymbol{r}_{ijk} = \boldsymbol{r}^{(1)}_{ijk} + \boldsymbol{r}^{(2)}_{ijk}$$

Electro-optic effect: linear changes of optical indicatrix coefficient

$$a_{10}x^2 + a_{20}y^2 + a_{30}z^2 = 1$$

$$a_{10} = \frac{1}{n_x^2},\ a_{20} = \frac{1}{n_y^2},\ a_{30} = \frac{1}{n_z^2}$$

$$\boxed{\Delta_k = a_k - a_{k0} = r_{k1}E_x + r_{k2}E_y + r_{k3}E_z} \qquad k = 1, 2, \ldots, 6$$

$$\Delta_k = a_k - a_{k0} = \sum_{l=1}^{3} r_{kl}E_l \qquad \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \Delta_5 \\ \Delta_6 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

Electro optic effect: refractive index changes

$$\Delta_k = a_k - a_{k0} = \frac{1}{n_k^2} - \frac{1}{n_{ko}^2} = \bar{\bar{r}}\vec{E}$$

$$\bar{\bar{r}}\vec{E} = \frac{1}{n_k^2} - \frac{1}{n_{ko}^2} = \frac{n_{ko}^2 - n_k^2}{n_k^2 n_{ko}^2} = \frac{(n_{ko} - n_k)(n_{ko} + n_k)}{n_k^2 n_{ko}^2}$$

$$\approx \frac{\Delta n 2 n_{ko}}{n_{ko}^4} = \frac{2\Delta n}{n_{ko}^3}$$

$$\Delta n = \frac{1}{2} n_{ko}^3 \bar{\bar{r}}\vec{E} \qquad \Delta n = \frac{1}{2} n^3 r \frac{U}{d}$$

4. <u>Photorefractive effect</u>

The photorefractive effect was accidentally discovered in 1966 in $LiNbO_3$ and $LiTaO_3$ as detrimental optically induced refractive index inhomogeneities. It was referred to as "optical damage" because it caused a degradation of the performance of nonlinear optical devices based on these materials. Two years later, holographic optical storage has been demonstrated in $LiNbO_3$ using this newly discovered effect. In 1969, Chen proposed a model based on the migration of photoexcited electrons which explained the main experimental observations and set the basis for future experimental and theoretical work. The term photorefractive, which literally means light induced change of the refractive index, was introduced later on and since then has been reserved for this particular mechanism.

In 1976, Kukhtarev et al. derived the dependence of the refractive index change on light intensity and material parameters and described the coupling of beams in thick photorefractive gratings. Today, almost 30 years after its first discovery, photorefractivity is a blooming field of interdisciplinary research. Over the years several materials like $BaTiO_3$, $KNbO_3$, $Bi_4Ti_3O_{12}$, $Sr_{1-x}Ba_xNb_2O_6$ (SNB), $Ba_{2-x}Sr_xNa_yNb_5O_{12}$ (KNSBN), $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}GeO_{20}$ (BGO), GaAs, InP, CdTe, $(Pb,La)(Zr,Ti)O_3$ and many other have been shown to exhibit the photorefractive effect, which makes it a quite general property of electrooptic crystals. Numerous applications in optical data storage, image processing and amplification, self and mutually pumped phase conjugation, photorefractive resonators, programmable optical interconnects, simulation of neural networks etc. have been proposed and demonstrated on a laboratory scale. Apart from potential applications, intensive research has been triggered for the understanding of the microscopic origin of the photorefractive effect, resulting in the discovery of new phenomena, such as the bulk photovoltaic effect and the excited state polarization.

Today, the mechanism of photorefractivity, although not fully, is quite well understood. This led to the recent observation of photorefractivity in new classes of materials such as organic crystals, polymers and liquid crystals. In figure 3., the basic mechanism is explained. The photorefractive effect is observed in materials which are both electrooptic and photoconducting. If such a sample is illuminated with a nonuniform light intensity pattern resulting from the interference of two mutually coherent beams, charge generation will take place at the bright areas of the fringes. These photogenerated charges will migrate and eventually get trapped at the dark areas, a process which can take place through several circles of photogeneration, diffusion and trapping. The resulting charge redistribution creates an internal electric field, the space charge field, which changes the refractive index via the electrooptic effect.

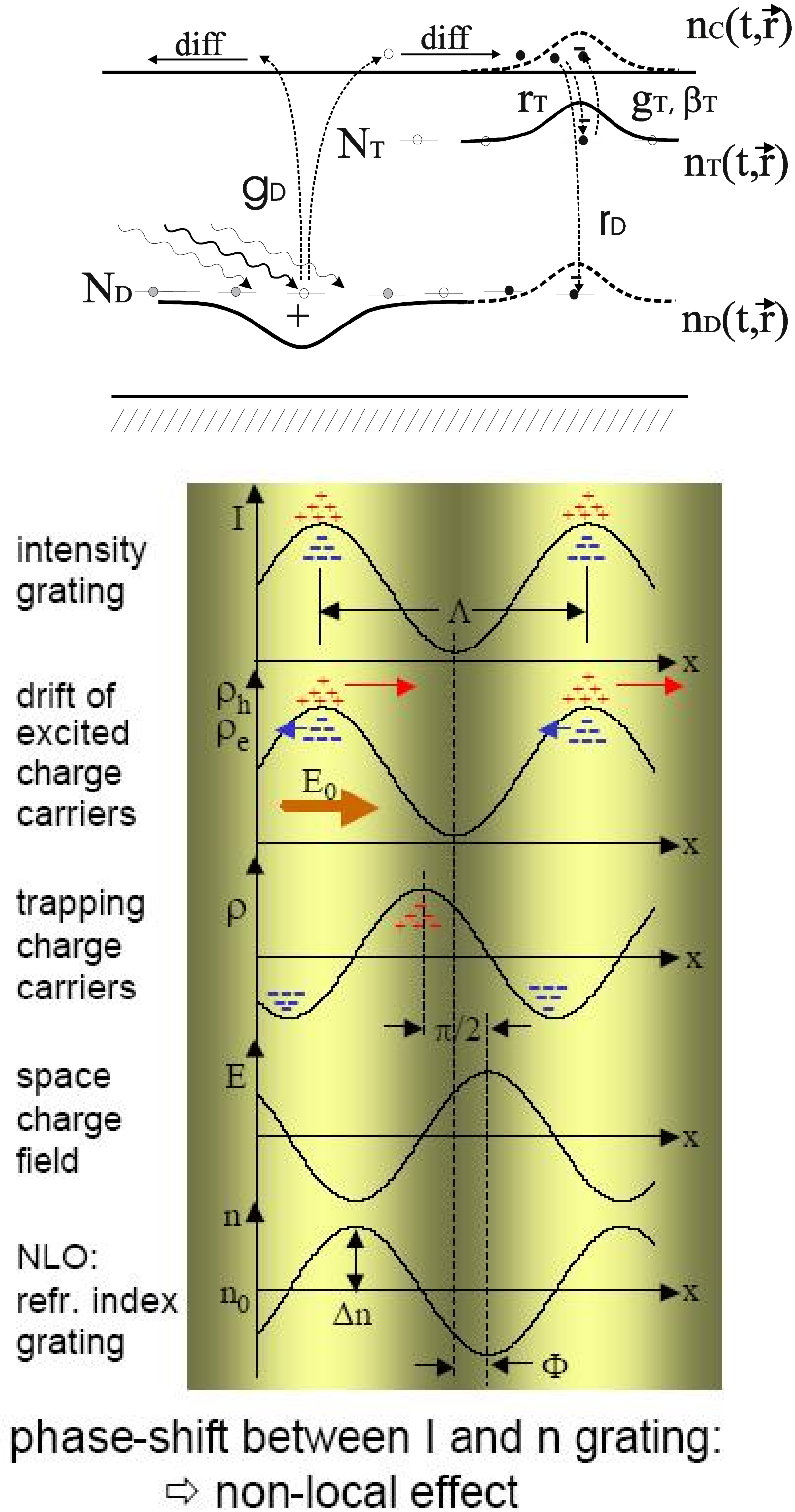
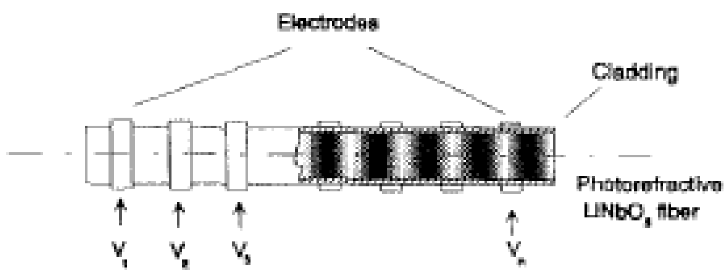


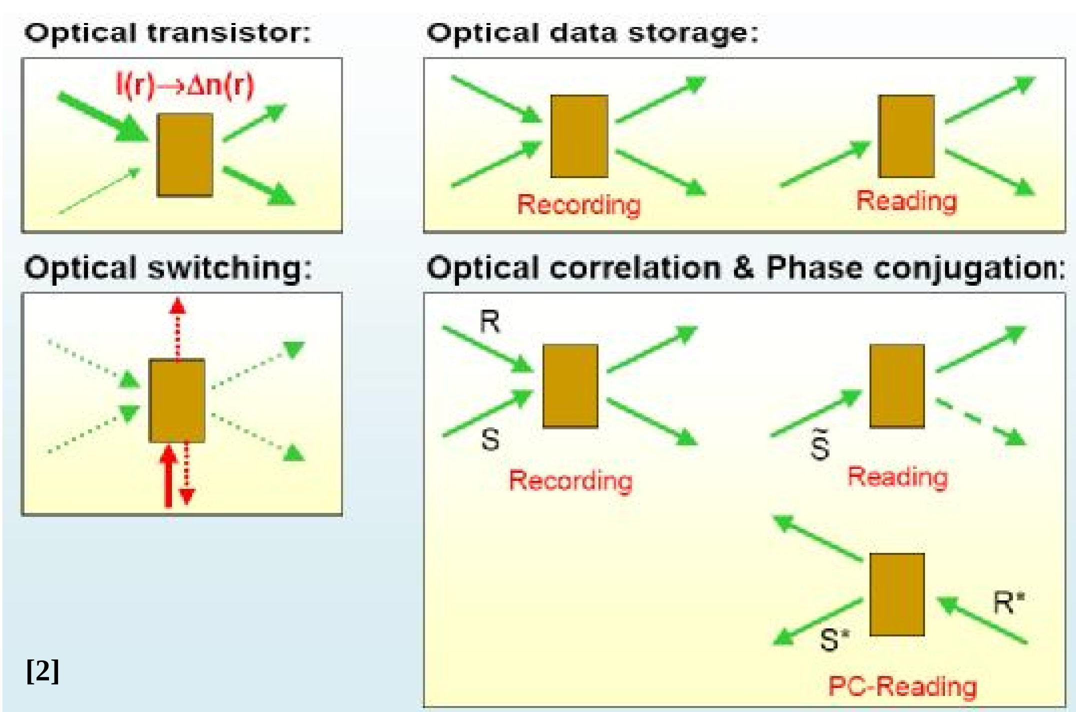
Fig. 3 *Basic mechanism of PRE*

5. Applications

- EO modulator
- switching elements
- optical filters
- optical data storage (holographic memories)
- waveguides
- multiplexer, demultiplexer
- resonators for tunable lasers
- and more…

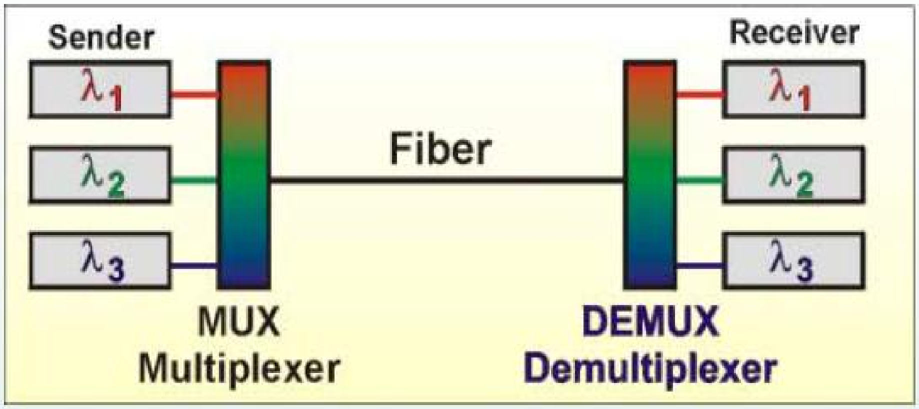


[1] . A sketch of a tunable fiber switch.



[2]

Wavelength division multiplexing (WDM):



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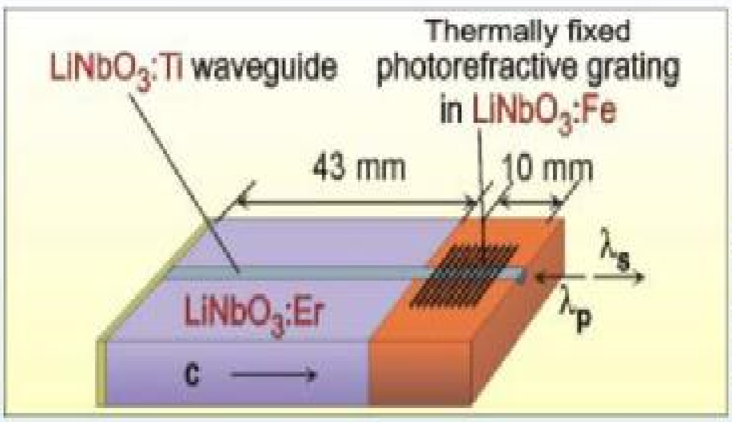
Compact cw DBR ("distributed Bragg reflection") laser with thermally fixed mirror grating:

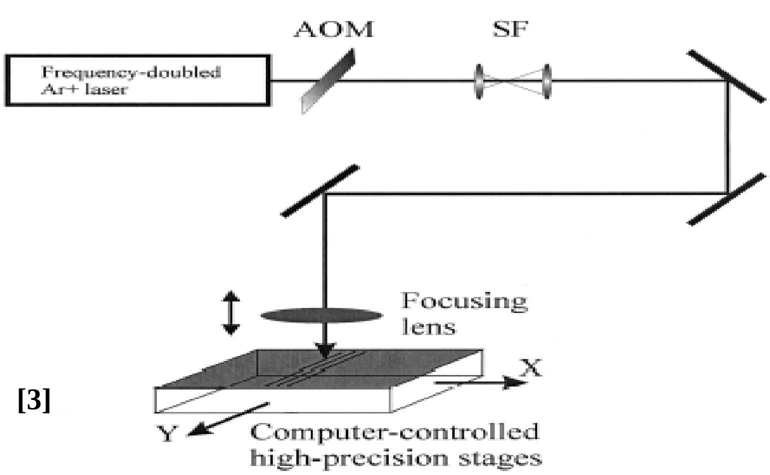


External optical pumping since $LiNbO_3$ has an indirect band gap

Ti indiffused waveguide yields high light intensities → Low pumping threshold, high efficiency

Fe doping: Photorefractive grating for DBR laser

Ch. Becker et al., *Opt. Lett.* **23**, 1194 (1998)



[3]

[1] F.T.S. Yu, A.S.Bhalla, S.Yin, F. Zhao, Z. Wu, D.M. Salerno, “Ce:Fe:LiNbO3 Photorfractive Crystal: Material Properties and Applications”, IEEE 1995, p. 636 – 641

[2] http:// www.physik.uni-bonn.de/hertz/Papers/buse.pdf

[3] S. Mailis, C. Riziotis, I. T. Wellington, P. G. R. Smith, C. B. E. Gawith, R. W. Eason, “Direct ultraviolet writing of channel waveguides in congruent lithium niobate single crystals”, Opt. Lett. Vol. 28 No. 16, 2003, p. 1433 – 1435