

*18.4 PHOTOREFRACTIVE MATERIALS

Photorefractive materials exhibit photoconductive and electro-optic behavior, and have the ability to detect and store spatial distributions of optical intensity in the form of spatial patterns of altered refractive index. Photoinduced charges create a space-charge distribution that produces an internal electric field, which, in turn, alters the refractive index by means of the electro-optic effect.

Ordinary *photoconductive* materials are often good insulators in the dark. Upon illumination, photons are absorbed, free charge carriers (electron-hole pairs) are generated, and the conductivity of the material increases. When the light is removed, the process of charge photogeneration ceases, and the conductivity returns to its dark value as the excess electrons and holes recombine. Photoconductors are used as photon detectors (see Sec. 17.2).

When a *photorefractive* material is exposed to light, free charge carriers (electrons or holes) are generated by excitation from impurity energy levels to an energy band, at a rate proportional to the optical power. This process is much like that in an extrinsic photoconductor (see Sec. 17.2). These carriers then diffuse away from the positions of high intensity where they were generated, leaving behind fixed charges of the opposite sign (associated with the impurity ions). The free carriers can be trapped by ionized impurities at other locations, depositing their charge there as they recombine. The result is the creation of an inhomogeneous space-charge distribution that can remain in place for a period of time after the light is removed. This charge distribution creates an *internal* electric field pattern that modulates the local refractive index of the material by virtue of the (Pockels) electro-optic effect. The image may be accessed optically by monitoring the spatial pattern of the refractive index using a probe optical wave. The material can be brought back to its original state (erased) by illumination with uniform light, or by heating. Thus the material can be used to record and store images, much like a photographic emulsion stores an image. The process is illustrated in Fig. 18.4-1 for doped lithium niobate (LiNbO_3).

Important photorefractive materials include barium titanate (BaTiO_3), bismuth silicon oxide ($\text{Bi}_{12}\text{SiO}_{20}$), lithium niobate (LiNbO_3), potassium niobate (KNbO_3), gallium arsenide (GaAs), and strontium barium niobate (SBN).

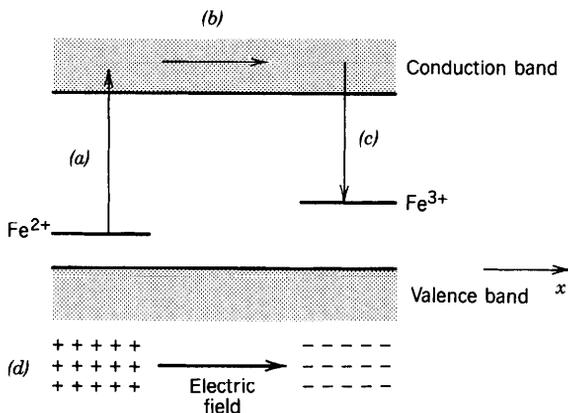


Figure 18.4-1 Energy-level diagram of LiNbO_3 illustrating the processes of (a) photoionization, (b) diffusion, (c) recombination, and (d) space-charge formation and electric-field generation. Fe^{2+} impurity centers act as donors, becoming Fe^{3+} when ionized, while Fe^{3+} centers act as traps, becoming Fe^{2+} after recombination.

Simplified Theory of Photorefractivity

When a photorefractive material is illuminated by light of intensity $I(x)$ that varies in the x direction, the refractive index changes by $\Delta n(x)$. The following is a step-by-step description of the processes that mediate this effect (illustrated in Fig. 18.4-1) and a simplified set of equations that govern them:

- **Photogeneration.** The absorption of a photon at position x raises an electron from the donor level to the conduction band. The rate of photoionization $G(x)$ is proportional both to the optical intensity and to the number density of nonionized donors. Thus

$$G(x) = s(N_D - N_D^+)I(x), \quad (18.4-1)$$

where N_D is the number density of donors, N_D^+ is the number density of ionized donors, and s is a constant known as the photoionization cross section.

- **Diffusion.** Since $I(x)$ is nonuniform, the number density of excited electrons $n(x)$ is also nonuniform. As a result, electrons diffuse from locations of high concentration to locations of low concentration.
- **Recombination.** The electrons recombine at a rate $R(x)$ proportional to their number density $n(x)$, and to the number density of ionized donors (traps) N_D^+ , so that

$$R(x) = \gamma_R n(x) N_D^+, \quad (18.4-2)$$

where γ_R is a constant. In equilibrium, the rate of recombination equals the rate of photoionization, $R(x) = G(x)$, so that

$$sI(x)(N_D - N_D^+) = \gamma_R n(x) N_D^+, \quad (18.4-3)$$

from which

$$n(x) = \frac{s}{\gamma_R} \frac{N_D - N_D^+}{N_D^+} I(x). \quad (18.4-4)$$

- **Space Charge.** Each photogenerated electron leaves behind a positive ionic charge. When the electron is trapped (recombines), its negative charge is deposited at a different site. As a result, a nonuniform space-charge distribution is formed.
- **Electric Field.** This nonuniform space charge generates a position-dependent electric field $E(x)$, which may be determined by observing that in steady state the drift and diffusion electric-current densities must be of equal magnitude and opposite sign, so that the total current density vanishes, i.e.,

$$J = e\mu_e n(x)E(x) - k_B T \mu_e \frac{dn}{dx} = 0, \quad (18.4-5)$$

where μ_e is the electron mobility, k_B is Boltzmann's constant, and T is the temperature. Thus

$$E(x) = \frac{k_B T}{e} \frac{1}{n(x)} \frac{dn}{dx}. \quad (18.4-6)$$

- *Refractive Index.* Since the material is electro-optic, the internal electric field $E(x)$ locally modifies the refractive index in accordance with

$$\Delta n(x) = -\frac{1}{2}n^3rE(x), \quad (18.4-7)$$

where n and r are the appropriate values of refractive index and electro-optic coefficient for the material [see (18.1-4)].

The relation between the incident light intensity $I(x)$ and the resultant refractive index change $\Delta n(x)$ may readily be obtained if we assume that the ratio $(N_D/N_D^+ - 1)$ in (18.4-4) is approximately constant, independent of x . In that case $n(x)$ is proportional to $I(x)$, so that (18.4-6) gives

$$E(x) = \frac{k_B T}{e} \frac{1}{I(x)} \frac{dI}{dx}. \quad (18.4-8)$$

Finally, substituting this into (18.4-7), provides an expression for the position-dependent refractive-index change as a function of intensity,

$$\Delta n(x) = -\frac{1}{2}n^3r \frac{k_B T}{e} \frac{1}{I(x)} \frac{dI}{dx}. \quad (18.4-9)$$

Refractive-Index
Change

This equation is readily generalized to two dimensions, whereupon it governs the operation of a photorefractive material as an image storage device.

Many assumptions have been made to keep the foregoing theory simple: In deriving (18.4-8) from (18.4-6) it was assumed that the ratio of number densities of unionized to ionized donors is approximately uniform, despite the spatial variation of the photoionization process. This assumption is approximately applicable when the ionization is caused by other more effective processes that are position independent in addition to the light pattern $I(x)$. Dark conductivity and volume photovoltaic effects were neglected. Holes were ignored. It was assumed that no external electric field was applied, when in fact this can be useful in certain applications. The theory is valid only in the steady state although the time dynamics of the photorefractive process are clearly important since they determine the speed with which the photorefractive material responds to the applied light. Yet in spite of all these assumptions, the simplified theory carries the essence of the behavior of photorefractive materials.

EXAMPLE 18.4-1. Detection of a Sinusoidal Spatial Intensity Pattern. Consider an intensity distribution in the form of a sinusoidal grating of period Λ , contrast m , and mean intensity I_0

$$I(x) = I_0 \left(1 + m \cos \frac{2\pi x}{\Lambda} \right), \quad (18.4-10)$$

as shown in Fig. 18.4-2. Substituting this into (18.4-8) and (18.4-9), we obtain the internal

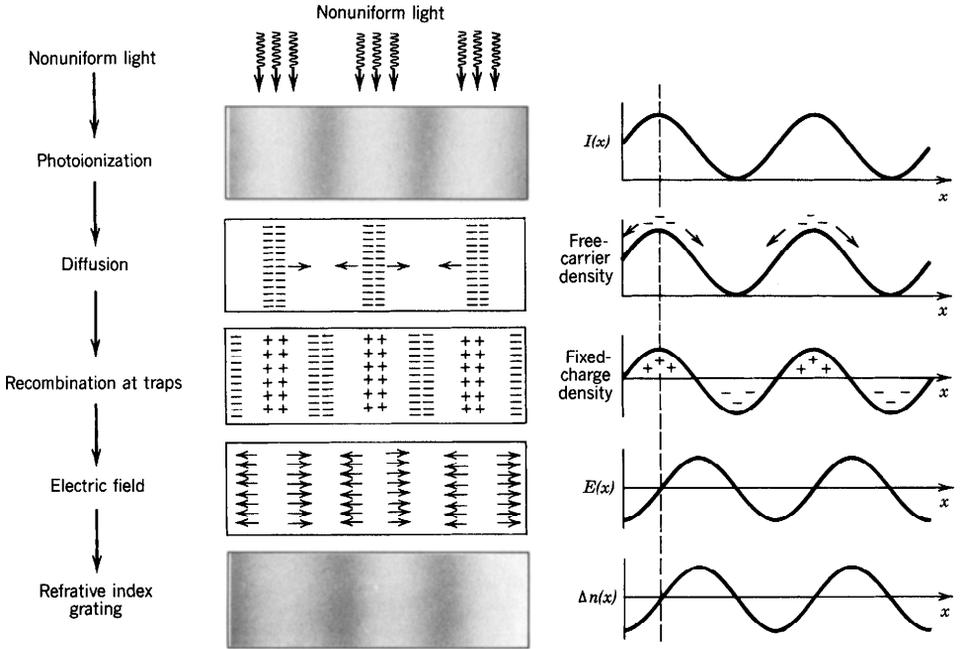


Figure 18.4-2 Response of a photorefractive material to a sinusoidal spatial light pattern.

electric field and refractive index distributions

$$E(x) = E_{\max} \frac{-\sin(2\pi x/\Lambda)}{1 + m \cos(2\pi x/\Lambda)}, \quad \Delta n(x) = \Delta n_{\max} \frac{\sin(2\pi x/\Lambda)}{1 + m \cos(2\pi x/\Lambda)}, \quad (18.4-11)$$

where $E_{\max} = 2\pi(k_B T/e\Lambda)m$ and $\Delta n_{\max} = \frac{1}{2}n^3\epsilon E_{\max}$ are the maximum values of $E(x)$ and $\Delta n(x)$, respectively.

If $\Lambda = 1 \mu\text{m}$, $m = 1$, and $T = 300 \text{ K}$, for example, $E_{\max} = 1.6 \times 10^5 \text{ V/m}$. This internal field is equivalent to applying 1.6 kV across a crystal of 1-cm width. The maximum refractive index change Δn_{\max} is directly proportional to the contrast m and the electro-optic coefficient ϵ , and inversely proportional to the spatial period Λ . The grating pattern $\Delta n(x)$ is totally insensitive to the uniform level of the illumination I_0 .

When the image contrast m is small, the second term of the denominators in (18.4-11) may be neglected. The internal electric field and refractive index change are then sinusoidal patterns shifted by 90° relative to the incident light pattern,

$$\Delta n(x) \approx \Delta n_{\max} \sin \frac{2\pi x}{\Lambda}. \quad (18.4-12)$$

These patterns are illustrated in Fig. 18.4-2.

Applications of the Photorefractive Effect

An image $I(x, y)$ may be stored in a photorefractive crystal in the form of a refractive-index distribution $\Delta n(x, y)$. The image can be read by using the crystal as a spatial-phase modulator to encode the information on a uniform optical plane wave

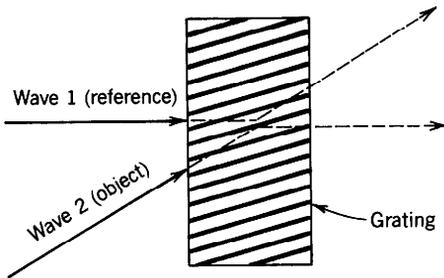


Figure 18.4-3 Two-wave mixing is a form of dynamic holography.

acting as a probe. Phase modulation may be converted into intensity modulation by placing the cell in an interferometer, for example.

Because of their capability to record images, photorefractive materials are attractive for use in real-time holography (see Sec. 4.5 for a discussion of holography). An object wave is holographically recorded by mixing it with a reference wave, as illustrated for two plane waves in Fig. 18.4-3. The intensity of the sum of two such waves forms a sinusoidal interference pattern, which is recorded in the photorefractive crystal in the form of a refractive-index variation. The crystal then serves as a volume phase hologram (see Sec. 4.5, Fig. 4.5-10). To reconstruct the stored object wave, the crystal is illuminated with the reference wave. Acting as a volume diffraction grating, the crystal reflects the reference wave and reproduces the object wave.

Since the recording process is relatively fast, the processes of recording and reconstruction can be carried out simultaneously. The object and reference waves travel together in the medium and exchange energy via reflection from the created grating. This process is called **two-wave mixing**. As shown in Fig. 18.4-3 (see also Fig. 4.5-8), waves 1 and 2 interfere and form a volume grating. Wave 1 reflects from the grating and adds to wave 2; wave 2 reflects from the grating and adds to wave 1. Thus the two waves are coupled together by the grating they create in the medium. Consequently, the transmission of wave 1 through the medium is controlled by the presence of wave 2, and *vice versa*. For example, wave 1 may be amplified at the expense of wave 2.

The mixing of two (or more) waves also occurs in other nonlinear optical materials with light-dependent optical properties, as discussed in Chap. 19. Wave mixing has numerous applications in optical data processing (see Chaps. 19 and 21), including image amplification, the removal of image aberrations, cross correlation of images, and optical interconnections.

READING LIST

General

- M. A. Karim, *Electro-Optical Devices and Systems*, PWS-Kent, Boston, 1990.
- A. Yariv, *Quantum Electronics*, Wiley, New York, 1967, 3rd ed. 1989.
- M. J. Weber, ed., *Optical Materials*, in *Handbook of Laser Science and Technology*, vol. IV, Part 2, CRC Press, Boca Raton, FL, 1986–1987.
- L. J. Pinson, *Electro-Optics*, Wiley, New York, 1985.
- A. Yariv, *Optical Electronics*, Holt, Rinehart and Winston, New York, 1971, 3rd ed. 1985.
- A. Yariv and P. Yeh, *Optical Waves in Crystals*, Wiley, New York, 1984.
- H. A. Haus, *Waves and Fields in Optoelectronics*, Prentice-Hall, Englewood Cliffs, NJ, 1984.