F85: Optik Grundpraktikum

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Abstract
This FP lab course serves as an introduction to three important properties of light waves: Polarization, phase and frequency are observed using commonly used optical components such as wave-plates, polarizing beam-splitters, electro-optical modulators and acousto-optical modulators.

The material we use as an optical medium in this course is $LiNbO_3$.

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2.1 Polarization

A beam of light can be described as a plane electromagnetic wave, like so:

$$\vec{E}(z,t) = E_0 \cdot \hat{e}_x \cdot e^{i(\omega t - kz)}$$

$$\vec{B}(z,t) = B_0 \cdot \hat{e}_y \cdot e^{i(\omega t - kz)}$$

The propagation vector $\hat{e}_z$ together with $\vec{E}$ and $\vec{B}$ create an orthogonal system.

The direction of $\vec{E}$ defines the polarization, which can be distinguished into three types:

1. linear polarization
2. elliptical polarization
3. circular polarization

If the wave is thought of as a superposition of two orthogonal plane waves, elliptical polarization occurs when the phase difference of those two waves is exactly $\Delta\varphi = \frac{\pi}{2}$. If, in addition, both waves carry the same amplitude, we speak of circular polarization. What happens for $\Delta\varphi \neq \frac{\pi}{2}$?

2.1.1 Snell's law

If a beam of light reaches the surface between two optical media with refractive indices n_1 and n_2, the beam splits into a reflected and a refracted one. The refraction angle α_2 can be determined by

$$n_1 \cdot sin(\alpha_1) = n_2 \cdot sin(\alpha_2)$$

The angles α_1 and α_2 are taken between the incoming/outgoing beam of light and the surface.

For reflection, the condition $\alpha_{in} = \alpha_{out}$ must hold.

2.1.2 Malus law

The Malus law states that when a perfect polarizer is placed in a polarized beam of light, the intensities before and after tranversing the polarizer are related by

$$I_f = I_i \cdot cos^2(\theta)$$

Here, θ is the angle between the light's initial polarization direction and the axis of the polarizer.

2.1.3 Brewster's angle

Brewster's angle is a specific angle of incidence at which light with a particular polarization is perfectly transmitted through a transparent dielectric surface, without any reflection.

When unpolarized light is incident at this angle, the light that is reflected from the surface is therefore perfectly polarized. Meaning? Sources?

2.1.4 Fresnel equations

The Fresnel equations describe the reflection and transmission of light when incident on an interface between different optical media. equations

2.1.5 Reflection and polarization

From Maxwell's equation the amplitudes and intensities of the two beams can be derived. The amplitude coefficients corresponding to the reflected and the transmitted beams are labeled r and t. The intensity coefficients R and T can easily be calculated by taking the square of r and t. If the polarization is perpendicular to the plane of incidence (transversal-electric, S-polarization), the coefficients are given by

$$r_{TE} = -\frac{sin(\alpha_1 - \alpha_2)}{sin(\alpha_1 + \alpha_2)}$$

and

$$t_{TE} = \frac{2 \cdot sin(\alpha_1) \cdot cos(\alpha_2)}{sin(\alpha_1 + \alpha_2)}$$

If the wave is polarized parallel to the plane of incidence, we speak of transversal-magnetic polarization (German: P-Polarisation), the coefficients are given by

$$r_{TM} = \frac{tan(\alpha_1 - \alpha_2)}{tan(\alpha_1 + \alpha_2)}$$

and

$$t_{TM} = \frac{2 \cdot sin(\alpha_1) \cdot cos(\alpha_2)}{sin(\alpha_1 + \alpha_2) \cdot cos(\alpha_1 - \alpha_2)}$$

2.1.6 Birefringence

2.1.7 Wave plates

2.2 Electro-optical effect

Some materials experience a change in their optical properties when they are brought into an external electric field. If the refractive index n is a function of the applied field E, we speak of an electro-optical modulator (EOM).

2.2.1 Pockels effect

The refractive index $n = n(E)$ can be expanded around $E = 0$ for small field strengths.

With $r = -\frac{2}{n^3}\left(\frac{dn}{dE}\right)\Big|_{E=0}$ and $s = -\frac{1}{n^3}\left(\frac{d^2n}{dE^2}\right)\Big|_{E=0}$, this leads to the relation

$$n(E) = n_0 - \frac{1}{2}rn^3E - \frac{1}{2}sn^3E^2$$

The linear electro-optical effect, also called Pockels effect, occurs for $r \gg s$:

$$n(E) \approx n_0 - \frac{1}{2}rn^3E$$

Here, r is called the Pockels coefficient. If, on the other hand, $r \ll s$, the quadratic dependence of n on E is known as the Kerr effect. This effect will not be studied in this lab course.

2.2.2 Pockels effect in a non-isotropic crystal

Since the electro-optical crystals are in general birefringent, the Pockels coefficient is not a scalar, but a tensor. For the material $LiNbO_3$, the entries of this coefficient-tensor are given by

$$\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{pmatrix} = \begin{pmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & -3.4 & 8.6 \\ 0 & 3.4 & 8.6 \\ 0 & 0 & 30.8 \\ 0 & 28 & 0 \\ 28 & 0 & 0 \\ -3.4 & 0 & 0 \end{pmatrix} \cdot 10^{-12}\ \frac{\mathrm{m}}{\mathrm{V}}$$

2.3 Acousto-optical effect

If a sound wave passes through a crystal, its density varies periodically, which also leads to a periodic variation in the refractive index. A plane sound wave with wavelength λ_s in a crystal with initial refractive index n_0 can be described by

$$n(x,t) = n_0 - \Delta n \cdot cos\left(\omega t - \frac{2\pi}{\lambda_s} x\right)$$

Here, the amplitude $\Delta n = \frac{1}{2} p n^3 s_0$ depends on the photo-elastic constant p and the amplitude of the strain s_0. The interaction between laser beam and sound wave occurs either as Bragg diffraction for long interaction lengths or as the Debye-Sears effect for short interaction lengths, i.e. for a thin crystal or thin sound beam. Parts of the light beam that are travelling through the denser

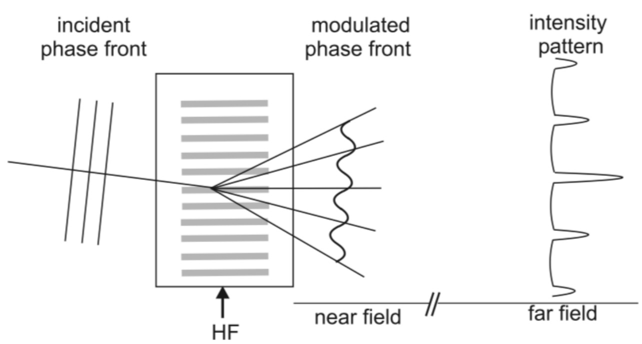

Figure 1: deformation of a plane wavefront by a sound wave

regions experience a phase shift. Maxima in the far field can be observed, if these parts of the beam interfere constructively with each other, as can be seen in the next figure. Because the light

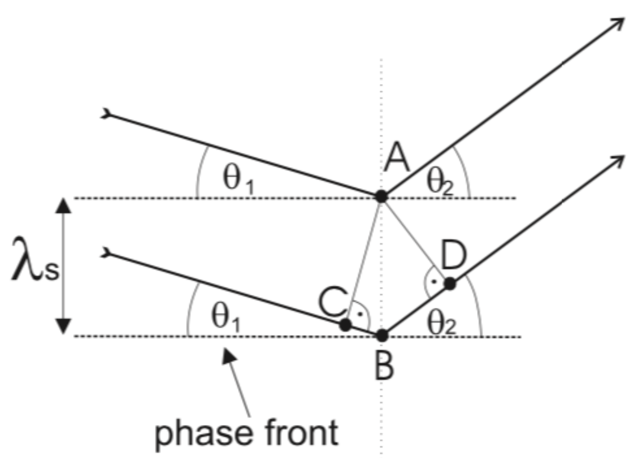

Figure 2: interference of different sections of the light beam

is interacting with a moving sound wave, the diffracted light is Doppler-shifted:

$$\omega_{out} = \omega_{in} + m\Delta\omega = \omega_{in} + m\omega_s$$

A different approach to explain the effect of an AOM on a light beam is to describe the system as two scattering quasi-particles, namely a phonon and a photon. Their momentum vectors are $\hbar\vec{k}_l$ and $\hbar\vec{k}_s$, respectively. Conservation of momentum and energy leads to the relations

$$\vec{k}_{l,f} = \vec{k}_{l,i} \pm m\vec{k}_s$$

and

$$\nu_{l,f} = \nu_{l,i} \pm m\nu_s$$

Here, m is the diffraction order, i.e. the number of phonons that interacted with the photon. Constructive interference occurs when

$$sin\theta_1 + sin\theta_2 = m\frac{\lambda}{\lambda_s}$$

Here, θ_1 is the angle under which light enters the crystal and θ_2 the diffraction angle. efficiency

3 Experiment

3.1 Polarizers and wave plates

3.2 Electro-optical effect

3.2.1 Phase shift due to electro-optical effect

3.2.2 Manipulation of polarization and intensity

3.3 Acousto-optical effect

- adjust AOM so that amplitude of diffraction pattern is approximately symmetric in both ± 1 orders

4 Results

5 Analysis

6 Summary

7 Discussion