

## 5.2.4 Polarization and Materials

### Linear Polarization

What kind of properties need a material have to have, so it *linearly* polarizes light?

- For starters: if you run the light *through* the material, it needs to be transparent. But who says that you can only polarize light by running it *through* a material? How about bouncing it off some material or, in other words, *reflecting* it at some mirror-like surface?
- This should trigger a flash-back. As you already know, it is perfectly possible to polarize light by utilizing reflection; just look once more at the [Fresnel equations](#).

All things considered, there are several ways to polarizes light, each one with its own requirements, advantages, and disadvantages. Here we'll just take a first glimpse at some major **polarizing methods**.

#### 1. Special geometries.

- As we have learned under the heading "[Fresnel equations](#)", a non-polarized light beam impinging on *any material* under some special angle ("[Brewster angle](#)") will produce a fully polarized *reflected* beam. Of course, some materials are more suitable than others (the index of refraction should have a decent value, not too close to  $n=1$  but not too large either) but no *special* properties of the materials are required.
- Using the "Brewster angle" approach is indeed a major way to produce polarized light. It is more or less limited to "advanced" application, however, because there are some problems. Time for a quick exercise:

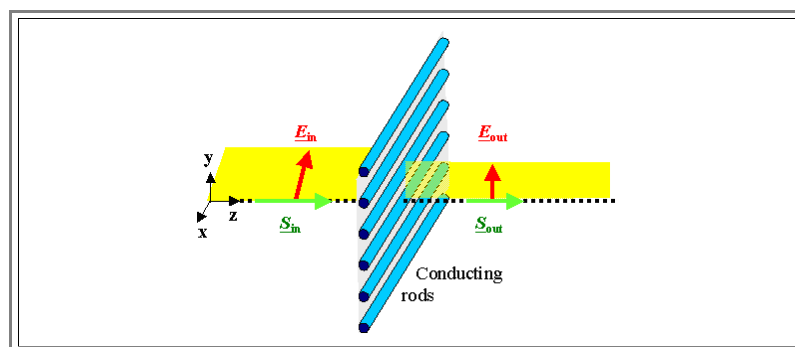
### Exercise 5.2.4

Polarizers based on reflection

- For everyday applications like your "Polaroid" sun glasses or the cheap glasses used for watching **3D** movies in the cinema, you need something less special and far, far cheaper. You need:

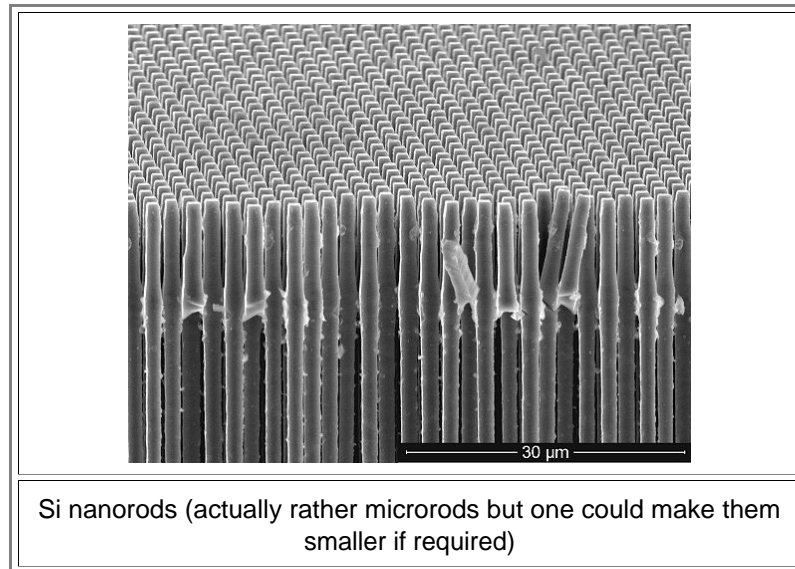
#### 2. Polarization filters or foils

- We have a typically thin and bendable transparent foil (or a thin unbendable glass-like sheet). Unpolarized light goes in from one side, *linearly* polarized light comes out on the other side. There are *two* basic ways or principles for that:
  - The material contains "nanorod" conductors arranged in a grid with dimensions in the wavelength region.
  - The material is "*birefringent*" or in neutral terms, it is *optically anisotropic*, meaning that  $\epsilon$  and therefore also  $n$  are *tensors*.
- The *bad* news are: The second principle is the more important one!  
The *good* news are: We are *not* going to look at that in great detail, since there is not enough time. Tensor optics also may cause the bulk intake of large quantities of alcohol to soothe your brain, and you are too young for this.
- The *first* principle is easy to understand:
  - Just imagine for a moment that you need to polarize *radio waves* with a wave length in the **cm** region and not light. All you need to do is to use a bunch of aligned **conducting rods** as shown below:



- Surprise!** The polarization direction is *not* parallel to the rods as one would naively imagine but **perpendicular** to it.
- It's clear what happens, though. The field components *parallel* to the conducting rods will simply be short circuited, causing currents  $\mathbf{j} = \sigma \mathbf{E}$  in the rod, and thus heating. The components *perpendicular* to the rods cannot cause much current and pass mostly through. The figure above, by the way, is identical to a figure we [had before](#) except that the symbolic polarizer in this picture has now materialized into a defined device or product.
- If you wonder about possible *diffraction* effects at the grid: There aren't any if the distance between the rods is smaller than a wavelength. Just do an [Ewald sphere](#) construction to see this.
- The priciple, of course, also works for the electromagnetic waves we call light. All that remains to do, is to produce aligned conductive rods on a **100 nm** or so scale; **nanorods** in other words. *Any ideas?*

- Well, a guy named **Edwin Herbert Land** (1909 - 1991) had an idea - in 1932. Take a polymer foil that can easily be stretched to a large extent (look at [this link](#) to get an idea), get some proper stuff inside (microscopic **herapathite crystals** in Lang's case; funny things in their own right involving **dog piss**), and then stretch the whole foil, aligning the little crystals. Use [the link to get the full story](#).
  - I don't know what Lang thought when he did this. Some people (and text books) believe that he did **align conducting rods**, indeed. Chances are that he did not, however. The herapathite crystals in Lang's case are actually very complex crystals; their structure was found out only a few years ago. Herapathite (also known as Chininbisulfatpolyiodid) forms intrinsically **polarizing crystals**, and all the stretching of the foil just insured that their polarization axes were aligned.
- So back to square 1: **Any ideas** of how to align conducting **nanorods** on a **100 nm** or so scale?
- Of course you have an idea: Use the basic **micro** (or by now **nano**) technologies of [semiconductor technology](#) and produce something as shown in the picture below



- The rods shown consist of **Si** and they would certainly polarizes (**IR**) light besides doing a few more things (due to their 3-dim.arrangement). It's however not a practical way for cheap mass-production stuff. Moreover, while light coming out on the "other" side would certainly be linearly polarized, one can just feel that it would not be a lot of light that makes it through the structure. More about this structure (which was not made for optics but for something utterly different) in the [link](#).
- If we look a bit beyond "normal" optics into the far **UV** and **IR**, polarizing a beam is not all that easy and structures as shown above might be the "future" in this case. Here is [the link](#) for some more information about this.
- Time for the famous last word: I could not find out in April 2011 if there are actually (cheap) polarizing foils out there that actually work on the "conducting rod" principle. So let's go for a **third** way.

### 3. Polarizing materials

- A good polarizing material, e.g. some **crystal** and not a "foil", transmits an incoming beam without too much absorption and emits one **or even two** beams that are more or less polarized.
  - We can already make one statement about the properties such a material must have: All directions must **not be equal** since the polarization direction is per definition special. Isotropic materials like most amorphous stuff and **all cubic crystals**, thus **cannot** be polarizing materials.
  - A stretched polymer foil is no longer isotropic since the polymer chains now are somewhat aligned in the stretching direction. However, it will not necessarily polarize light. **Try it!** Stretch some suitable candy wrap and see if it now polarizes light. Changes are it will not. So just being structurally **anisotropic** is not a good enough condition for being a polarizer.
- That means we must now deal with not-so-simple Bravais lattices, crystals, or other structures. It also means that properties like the dielectric constant  $\epsilon_r$  and thus the index of refraction  $n$ , the conductivity  $\sigma_r$ , possible magnetic properties, the modulus of elasticity (Young's modulus) and so on are no longer simple **scalar** number but **tensors** of second, third or even fourth rank! We are now discussing crystalline **"optical tensor materials"**.
- Talk about opening a can of worms! Nevertheless, understanding and exploiting the tensor properties of materials (mostly crystals) is where the action is right now (2011), and where it will be for the foreseeable future. At this point I will only enumerate some of the important effects of tensor materials on polarization.

## Optical Anisotropy and Tensor Materials

The basic ideas are easy to state. First, if there is an optical anisotropy, it can take two basic forms (and then mixtures of the two, of course):

**1. The index of refraction depends on the crystal direction.** The optical effects resulting from this are called "**birefringence**" or **double refraction** (Latin: bi=two, twice, refringere=to break up, to refract).

**2. The absorption depends on the polarization (and the crystal direction).** In some directions far less light of some polarization will come out after travelling through a crystal of given thickness than light polarized in the other direction. This effect is called **dichroism** (Greek for two-colored).

It is an unfortunate word because historically it was used first for a **different** effect: White light is split into into distinct beams of different wavelengths because of the crystal anisotropy and this is completely different from regular dispersion! Since the absorption effect may strongly depend on the wavelength, too, everything can be mixed up wonderfully. The word "**pleochroism**" ("more-colored") is occasionally used as a more general term, containing all of the above.

You know, of course (?) that the two effects must be related because they must both be contained in the complex index of refraction, which simply (haha) happens to be a **tensor** now. All tensor components are functions of the wavelength because we still have **dispersion** and, since we also have the **Fresnel equations**, they must be functions of the polarization, too

All we need to do now is to run through the derivation of the Fresnel equations once more. Just consider now a complex index of refraction that is also a tensor of of second rank with a symmetry that is somehow related to the crystal symmetry instead of a scale for boundary conditions and propagation. That would be a program that could entertain (some of) us for many weeks - so we are not going to do it here.

It is important to realize, however, that with our modern computers this is actually an easy task. As soon as a basic program has been written, and the functions describing the tensor components of the complex index are inputted, the rest is child's play. That's why for you, the young Materials Science and Engineer, the complex index is so important. For old guys like me it was not important, since we simply couldn't do the necessary math with a slide ruler as the only math tool. We had to resort to approximations and special case studies, and that's where all these fancy names and distinctions comes from.

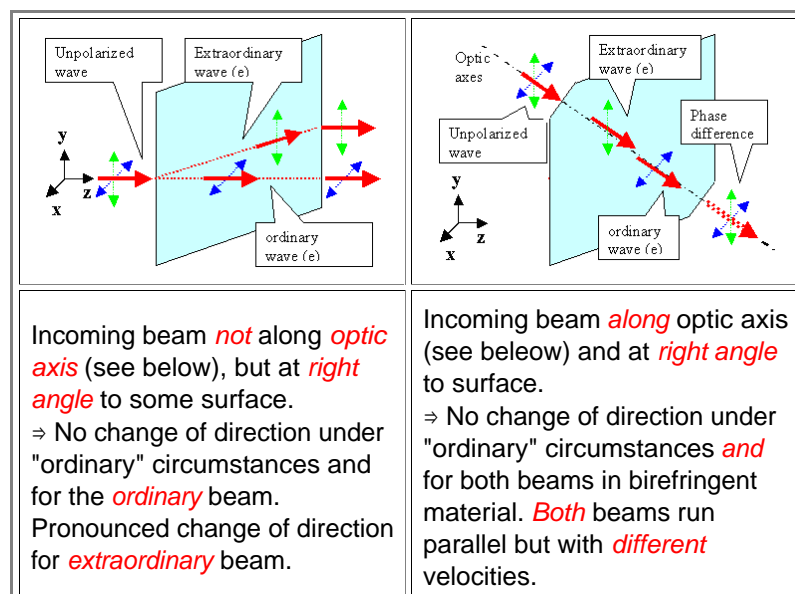
We are going to give the whole topic just a very superficial look, focussing on the practical side. As a first simplification we simply ignore di- or pleochroism for the time being and only give **birefringence** a slightly closer look. We also ignore absorption and thus the imaginary part of the complex index of refraction.

Recalling the little bit what **we know** about tensors, we are certain that there is always a coordinate system or "axes", where only the diagonal elements of the refractive index tensor are different from zero. These axes we call the **principal axes** of the crystal under consideration.

We then can always define **three principal refractive indices**  $n_1$ ,  $n_2$ ,  $n_3$  as the tensor components in the principal axes system. Note that those  $n$ 's will depend on the polarization and the wavelength. Of course, the principle axes will be related to the symmetry of the crystal in some way.

The rest is math. Not too difficult if you are used to tensor algebra but a bit mind boggling for normal people like us. For example, the dielectric displacement  $\mathbf{D}$  or the Poynting vector  $\mathbf{S}$  may no longer be parallel to the electrical field  $\mathbf{E}$  or the wave vector  $\mathbf{k}$ , respectively. Now what would that mean?

Be that as it may, the fact of importance here is that **in general**, an unpolarized light beam entering an anisotropic crystals splits into **two** orthogonally polarized light beams inside the birefringent material (typically a single crystal, a collection of small aligned single crystals, or an amorphous foil "somehow" made anisotropic and birefringent). **Two** different light beams thus will run through the crystal and eventually exit on the other side as shown below.



The two figures above illustrate the basic effects that will occur. It is best to discuss birefringences for the two special cases shown

**1. case:** The incoming (unpolarized) beam is *not* parallel to a principal axis of the crystal but its angle of incidence is  $90^\circ$ , i.e. it is exactly perpendicular to the surface of the crystal. This is a special condition, but not so very special because it is easy to do in an experiment, All you need are some flat surfaces.

- For an *isotropic* material with a *scalar* index of refraction  $n$  we know that there will be no *refraction* or bending of the beam. A little bit will be reflected (see the *Fresnel equation*), and the *polarization does not matter*. The transmitted beam will travel through the material at a velocity  $c=c_0/n$ .
- Exactly the same thing happens for the **ordinary wave** or **o-wave** in our tensor material here. However, the **o-wave** now is *fully polarized* as shown
- But in major contrast to isotropic materials with a scalar  $n$ , an *extraordinary* thing happens in our birefringent material with a *tensor*  $n$ . An **extraordinary wave** or **e-wave** is also generated at the interface. This **e-wave** travels under some angle with a velocity that is *different* from that of the **o-wave**. The **e-wave** is also *fully polarized*, but with a direction orthogonal to that of the **o-wave**.

**2. case:** The incoming (unpolarized) beam is *parallel* to an *optical axis* of the crystal, and its angle of incidence is still  $90^\circ$ , i.e. it is exactly perpendicular to the surface of the crystal. This is a rather special condition now because it means that our crystal must have a planar surface perpendicular to an special crystal direction.

- The so-called **optic axis** of the birefringent crystal is coupled to our *principal axes* from above. We have something new now (or just an extreme case of the general situation).
- The **o-wave** *and* the **e-wave** travel in the *same* direction=optic axis but with *different velocities*. Both waves are still fully polarized in orthogonal directions.
- The two waves emerging from the crystal then have *different phases*. The exact phase difference depends on the distance covered inside the material, i.e. on the thickness of the material.

That's just a description of what you will observe, of course. Calculating the relative intensities of the two beams, the intensities of reflected beams (??? (there is only one)), the two angles of refraction, the polarization directions, and the propagation velocities from the index of refraction tensor is possible, of course—but well beyond our scope here.

- One question remains: How many optic axes are there? The answer is: *Two* for "fully" anisotropic material and *one* for somewhat more symmetric materials. That tells you that the optic axis and the principal axis are not the same thing because we always have *three* principal axes. It's all in the table below.

Dielectric tensor in <i>principal axes</i>			
Anisotropic Materials		Isotropic Materials	
$\epsilon_r = \begin{pmatrix} \epsilon_1 & 0 & 0 \\ 0 & \epsilon_2 & 0 \\ 0 & 0 & \epsilon_3 \end{pmatrix}$	$\epsilon_r = \begin{pmatrix} \epsilon_1 & 0 & 0 \\ 0 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_3 \end{pmatrix}$	$\epsilon_r = \begin{pmatrix} \epsilon_1 & 0 & 0 \\ 0 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_1 \end{pmatrix}$	
General case <b>Two</b> optical axes	Practical case <b>One</b> optical axis		Simple case <b>All</b> directions / axes are equal
Mica	$\epsilon_3 > \epsilon_1$ Positive uniaxial	$\epsilon_3 < \epsilon_1$ Negative uniaxial	Glass Diamond Cubic crystal (NaCl, CaF <sub>2</sub> , Si, GaAs, ..)
	Ice quartz TiO <sub>2</sub> (rutile)	Calcite (CaCO <sub>3</sub> ) Tourmaline LiNbO <sub>3</sub>	

I can't end this chapter without a quick reference to the ubiquitous direct effect of birefringent crystals discovered long ago. There is deceptively simple effect already *known to Huygens and Co*: Take an "*Iceland spar*" crystal (**CaCO<sub>3</sub>** or **calcite**; easy to get), put it on some paper with writing on it and you see everything *twice* (see below).

- Here are some pictures taken in my office:



## Circular and Elliptical Polarization

- The topic is now to produce circular and elliptical polarization. This is easy because we already did that [just above](#) where we read: "*The two waves emerging from the crystal then have **different phases***"
- That sentence addressed the ordinary and extraordinary beam traveling in **parallel** along one of the two (or just the one) optic axes of a birefringent crystal.
  - The two beams travel in parallel—but with different speeds. So they have different phases at **different depths**. If we want **circular** polarized light, we just have to make sure that the thickness of the material we use has the right value for a [phase difference](#) of  $\pi/2$  between the two beams. The beams emerging then have exactly the phase difference needed for circular polarization.
- So far - so easy. Now let's do it in reality. You need a circular polarizer, and you now have all this textbook knowledge. What's next?
- Easy. You look into proper catalogues and buy a "**quarter lambda plate**" with a thickness ***d*** given by

$$(n_e - n_o) \cdot d = \lambda/4$$

- Then you laminate it with a linear polarizer to make sure that only light polarized in a certain direction enters the quarter lambda plate. What you get is one part of the glasses you get for watching 3-dim. movies. Alternatively, you just take those glasses with you, and you have two circular polarizers (plus the linear ones) for free. Don't ask me, how it is possible to make those optical components for very little money. I don't know—but intend to find out.

### Questionnaire

Multiple Choice questions to 5.2.4