530192 “Photonics in semiconductors”,
(5 op / 3 ov),
period III and IV – Spring 2017

**Lecturer:** Docent Ivan Kassamakov,
**Assistant:** Risto Montonen and Anton Nolvi, Doctoral students

Course webpage:
Personal information

- Ivan Kassamakov
  - e-mail: ivan.kassamakov@helsinki.fi
  - office: PHYSICUM - PHY C 318 (9:00-19:00)

- Risto Montonen
  - e-mail: risto.montonen@helsinki.fi
  - office: PHYSICUM - PHY A312

- Anton Nolvi
  - e-mail: anton.nolvi@helsinki.fi
  - office: PHYSICUM - PHY C 317
Schedule

- Lectures:
  Thursdays: 10:15 – 12:00, 19.01.2015 – 04.05.2017,
  Lecture Room: PHYSICUM - PHY D116 SH;

- Exercises:
  Thursdays: 14:15 – 16:00, 19.01.2015 – 04.05.2017,
  Lecture Room: PHYSICUM - PHY D114 SH;

- Demonstrations:
  Electronics Laboratory: PHYSICUM - PHY C 312 - 316
<table>
<thead>
<tr>
<th>Lecture #</th>
<th>Place - Lecture Room</th>
<th>Week #</th>
<th>Date</th>
<th>Starting time</th>
<th>Ending time</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>3</td>
<td>19.1.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>02</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>4</td>
<td>26.1.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>03</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>5</td>
<td>02.2.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>04</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>6</td>
<td>09.2.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>05</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>7</td>
<td>16.2.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>06</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>8</td>
<td>23.2.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>07</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>9</td>
<td>02.3.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>08</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>11</td>
<td>16.3.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>09</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>12</td>
<td>23.3.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>10</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>13</td>
<td>30.3.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>11</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>14</td>
<td>06.4.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>12</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>16</td>
<td>20.4.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>13</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>17</td>
<td>27.4.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>14</td>
<td>FOTONIIKKA PUOLIJHOTEISSA PHYSICUM - PHY D116 SH</td>
<td>18</td>
<td>04.5.2017</td>
<td>10:15</td>
<td>12:00</td>
</tr>
<tr>
<td>Exercise #</td>
<td>Place - Lecture Room</td>
<td>Week #</td>
<td>Date</td>
<td>Starting time</td>
<td>Ending time</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
<td>--------</td>
<td>-----------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>01</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>3</td>
<td>19.1.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>02</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>4</td>
<td>26.1.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>03</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>5</td>
<td>02.2.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>04</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>6</td>
<td>09.2.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>05</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>7</td>
<td>16.2.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>06</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>8</td>
<td>23.2.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>07</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>9</td>
<td>02.3.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>08</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>11</td>
<td>16.3.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>09</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>12</td>
<td>23.3.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>10</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>13</td>
<td>30.3.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>11</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>14</td>
<td>06.4.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>12</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>16</td>
<td>20.4.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>13</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>17</td>
<td>27.4.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
<tr>
<td>14</td>
<td>FOTONIIKKA PUOLIJOHTEISSA PHYSICUM - PHY D114 SH</td>
<td>18</td>
<td>04.5.2017</td>
<td>14:15</td>
<td>16:00</td>
</tr>
</tbody>
</table>

The breakdown of the general topics to be covered is:

1. Wave Nature of Light.
2. Dielectric Waveguides and Optical Fibers.
5. Photodetectors & Image Sensors.
6. Polarization and Modulation of Light.

www.booky.fi
They have very student friendly prices and fast delivery.

Heidi.Strommer@pearson.com
MacroSim is open source, GPU accelerated ray tracing engine. Originally developed for fast non-sequential stray light analysis of a spectrometer system, it offers the possibility to trace geometric rays sequentially and non sequentially with 64 bit floating point precision.

http://www.ito.uni-stuttgart.de/software/macroSim/
nLIGHT’s manufacturing facility in Lohja, Finland is approximately 1.900 m² with a clean room environment, including areas for preform manufacturing, fiber drawing, fiber measurement and testing, and optical engine assembly.
Lecture 01

Wave Nature of Light
Optics is an old subject involving the generation, propagation & detection of light.

Three major developments are responsible for rejuvenation of optics & its application in modern technology:

1. Invention of Laser
2. Fabrication of low-loss optical Fiber
3. Development of Semiconductor Optical Device

As a result, new disciplines have emerged & new terms describing them have come into use, such as:

- Electro-Optics: is generally reserved for optical devices in which electrical effects play a role, such as lasers, electro-optic modulators & switches.
Photonics: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The science includes light emission, transmission, deflection, amplification and detection by optical components and instruments, lasers and other light sources, fiber optics, electro-optical instrumentation, related hardware and electronics, and sophisticated systems. The range of applications of photonics extends from energy generation to detection to communications and information processing.

from the Photonics Dictionary at Photonics.com
**Photonics** (in general): involves the control of photons in free space and matter.

- **1- Generation of Light** (coherent & incoherent)
- **2- Transmission of Light** (through free space, fibers, imaging systems, waveguides, …)
- **3- Processing of Light Signals** (modulation, switching, amplification, frequency conversion, …)
- **4- Detection of Light** (coherent & incoherent)
An electromagnetic wave is a travelling wave which has time varying electric and magnetic fields which are perpendicular to each other and the direction of propagation, $z$. 
Light Wave

Plane electromagnetic wave (traveling wave)

\[ E_x(z,t) = E_0 \cos (\omega t - k z + \phi_0) \]

\[ = \text{Re}[E_0 \exp(j\phi_0) \exp j(\omega t - k z)] \]

\[ = \text{Re}[E_c \exp j(\omega t - k z)] \]

- \( k \): propagation constant or wave number \( k=2\pi/\lambda \)
- \( \omega \): angular frequency
- Phase of the wave \( (\omega t - k z + \phi_0) \)
- \( E_x = E_0 \exp(j\phi_0) \) is a complex number that represents the amplitude of the wave and includes the constant phase information \( \phi_0 \).

- **Wave front**: A surface over which the phase of a wave is constant.
- **Optical field**: refers to the electrical field \( E_x \).

An electromagnetic wave is a travelling wave which has time varying electric and magnetic fields which are perpendicular to each other and the direction of propagation, \( z \).

**Traveling wave along** \( z \)**
A plane EM wave travelling along $z$, has the same $E_x$ (or $B_y$) at any point in a given $xy$ plane. All electric field vectors in a given $xy$ plane are therefore in phase. The $xy$ planes are of infinite extent in the $x$ and $y$ directions.
Plane Electro-magnetic wave with E field along x, traveling along z.
Wave Vector, $\mathbf{k}$: Use to indicate the direction of propagation. The vector whose direction is normal to the wavefront, and magnitude is $k = \frac{2\pi}{\lambda}$.

$$\mathbf{k} \cdot \mathbf{r} = k_x x + k_y y + k_z z$$

Hence the electric field in a perpendicular plane to $\mathbf{k}$ in a point $\mathbf{r}$ can be expressed by:

$$E_x (\mathbf{r}, t) = E_0 \cos (\omega t - \mathbf{k} \cdot \mathbf{r} + \phi_0)$$

In general, from the definition of the dot product, $\mathbf{k} \cdot \mathbf{r} = k_x x + k_y y + k_z z$
Phase velocity

The Electric field $E_x$ shows constant values when the phase is constant (cosine argument).

$$E_x(z,t) = E_0 \cos(\omega t - k.z + \phi_0)$$

This happens when the spatial-temporal condition is fulfilled:

$$\phi = (\omega t - k.z + \phi_0) = \text{const}$$

In the time interval $\delta t$ the constant phase moves of an amount of $\delta z$. Hence we can define the phase velocity as:

$$v = \frac{dz}{dt} = \frac{\omega}{k} = v\lambda$$
Some Examples of EM Waves

Wave fronts (constant phase surfaces)

A perfect plane wave

A perfect spherical wave

A divergent beam

The amplitude of the **planar wave** $E_o$ does not depend on the distance from a reference point, and it is the same at all points on a given plane perpendicular to $k$, i.e. independent of $x$ and $y$. As these planes extend to infinity there is infinite energy in the plane-wave.

A **spherical wave** is described by a traveling field that emerges from a point EM source and whose amplitude decays with distance $r$ from the source.

**Optical divergence** refers to the angular separation of wavevectors on a given wave front.

A plane-wave may be a small part of a "huge" spherical wave.
Some Examples of EM Waves

Wave fronts (constant phase surfaces)

A perfect plane wave

A perfect spherical wave

A divergent beam

All EM must obey Maxwell's EM wave equation:

\[
\frac{\partial^2 E}{dx^2} + \frac{\partial^2 E}{dy^2} + \frac{\partial^2 E}{dz^2} = \varepsilon_0 \varepsilon_r \mu_0 \frac{\partial^2 E}{dt^2}
\]

We assume that the conductivity of the medium is zero.
To find the time and space dependence of the field, we must solve the equation in conjunction with the initial and boundary conditions.

\(\varepsilon_r = \text{relative permittivity,}\)

\(\varepsilon_0 = \text{absolute permittivity,}\)

\(\mu_0 = \text{absolute permeability}\)
The radiation emitted from a laser can be approximated by a Gaussian beam. Gaussian beam approximations are widely used in photonics.

The finite width $2w_0$ where the wavefronts are parallel is called the waist of the beam;

Wavefronts of a Gaussian light beam
The beam has an \(\exp(j(wt-kz))\) dependence to describe propagation characteristics;

The amplitude varies spatially away from the beam axis and also along the beam axis.

The beam diameter \(2w\) at any point \(z\) is defined in such a way that the cross sectional area \(\pi w^2\) at that point contains 86\% of the beam power.

Thus the beam diameter \(2w\) increases as the beam travels along \(z\).
A Gaussian beam is the result of radiation from a source of finite extent.

A Gaussian beam shows the spot size \((2w_o)\) which depend to the beam divergence by the expression:

\[
2\theta = \frac{4\lambda}{\pi(2w_0)}
\]

\(\theta\) - beam divergence

The greater the waist, the narrower the divergence.

Suppose that we reflect the Gaussian beam back on itself so that the beam is travelling in the -z direction and converging towards O. The equation therefore defines a minimum spot size to which a Gaussian beam can be focused.
The $M^2$ factor measures the deviation of the real laser beam from the Gaussian characteristics, in which $M^2 = 1$ for an ideal (theoretical) Gaussian beam shape. Suppose that $2\theta_r$ and $2w_{or}$ are the divergence and waist, respectively, of the real laser beam, and $2\theta_o$ and $2w_o$ are those for the ideal Gaussian. The $M2$ factor is defined by:

$$M^2 = \frac{w_{or}\theta_r}{w_o\theta} = \frac{w_{or}\theta_r}{(\lambda/\pi)}$$

$$2w_r = 2w_{or}\left[1 + \left(\frac{z\lambda M^2}{\pi w_{or}^2}\right)^2\right]^{1/2}$$

![Diagram showing real and ideal Gaussian beams](image)
$I(r) = I(0) \exp(-2r^2/w^2)$
Example

- Consider a HeNe laser beam at 633 nm with a spot size of 10 mm. Assuming a Gaussian beam, what is the divergence of the beam?
When an EM wave is traveling in a dielectric medium, the oscillating electric field polarizes the molecules of the medium at the frequency of the wave. The field and the induced molecular dipoles become coupled. The net effect is that the polarization mechanism delays the propagation of the EM wave. In other words, it slows down the EM wave with respect to its speed in a vacuum. The stronger the interaction between the field and the dipole, the slower the propagation of the wave. The ratio of the speed of light in free space to its speed in a medium is called the refractive index $n$ of the medium. Definition of refractive index:

$$n = \frac{c}{V} = \sqrt{\varepsilon_r}$$

$V$ : phase velocity in a nonmagnetic dielectric medium  
$\varepsilon_r$ : relative permittivity

The variation of $n$ with direction of propagation and the direction of the electric field depends on the particular crystal structure. With the exception of cubic crystals (such as diamond), all crystals exhibit a degree of optical anisotropy that leads to a number of important applications.
Relative Permittivity

The relative permittivity (or the dielectric constant of material) measures the ease with which the medium becomes polarized and hence it indicates the extent of interaction between the field and the induced dipoles. Relative permittivity \( \varepsilon_r \) is the ratio of the permittivity of a specific medium to the permittivity of free space \( \varepsilon_0 \).

For an EM wave traveling in a nonmagnetic dielectric medium of relative permittivity \( \varepsilon_r \), the phase velocity \( \nu \) is given by:

\[
\nu = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_0}}
\]

For an EM wave traveling in free space of vacuum, \( \varepsilon_r = 1 \) and \( \nu_{\text{vacuum}} = c = 3 \times 10^8 \text{ ms}^{-1} \).

If \( k \) is the wave vector (\( k = 2\pi/\lambda \)) and \( \lambda \) is the wavelength in free space, then in the medium

\[
k_{\text{medium}} = nk \quad \text{and} \quad \lambda_{\text{medium}} = \lambda/n.
\]
When two slightly different in wavelength waves interfere, they generate a wave packet (or wave train) that contains an oscillating field at the mean frequency $\omega$ that is amplitude modulated by a slowly varying field of frequency $\delta \omega$. The maximum amplitude moves with a wave-vector $\delta k$ and thus with a velocity called group velocity:

$$v_g = \frac{d \omega}{d k}$$
In the vacuum the group velocity is equal to velocity of the light constant:

\[ v_g = \frac{d\omega}{dk} = c = \text{phase velocity} \]

When the wave travels into a medium where the refractive index is function of the wavelength (\( N_g \)), the group velocity is expressed by:

\[ v_g \text{(medium)} = \frac{d\omega}{dk} = \frac{c}{n - \lambda \frac{dn}{d\lambda}} = \frac{c}{N_g} \]
Dispersive Media

http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-further-dispersive.htm
The group velocity is the speed of the wave-packet and the phase velocity is the speed of the individual waves.
Refractive index $n$ and the group index $N_g$ of pure SiO$_2$ (silica) glass as a function of wavelength.

The group velocity defines the speed with which energy or information is propagated since it defines the speed of the envelope of the amplitude variation.

In vacuum, the group velocity is equal to phase velocity.

Around 1300 nm, $N_g$ is minimum, which means that for wavelengths close to 1300 nm, $N_g$ is wavelength independent. Thus, light waves with wavelengths around 1300 nm travel with the same group velocity and do not experience dispersion.

$$N_g = n - \lambda \frac{dn}{d\lambda}$$
Snell’s Law

A light that travels from a medium with a higher refractive index to a lower refractive index \((n_1 > n_2)\) produces a reflection and a refraction light at the boundary interface between the two medium.

\[
\frac{\sin(\theta_i)}{\sin(\theta_r)} = \frac{v_1}{v_2} = \frac{n_2}{n_1}
\]
Snell’s Law

\[ \frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \]

http://www.met.rdg.ac.uk/clouds/maxwell/
The amount of the reflected and refracted light depend on the incident angle.

a) Exist reflected and refracted light: $\theta_i < \theta_c$

b) There is not refracted light: $\theta_i = \theta_c$

c) There is evanescent light $\theta_i > \theta_c$ (TIR condition).

$$\sin(\theta_c) = \frac{n_2}{n_1}$$

Schematic presentation of an evanescent wave

http://dx.doi.org/10.1016/j.rbmret.2007.11.019
Evanescence Waves

$\Theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right) = 41^\circ$, incidence angle = 45°

http://www.met.rdg.ac.uk/clouds/maxwell/
Huygens’ Wave Construction

• wavefronts propagate from initial disturbance in all directions
• each point on the wavefront acts as a secondary source
• further wavefronts propagate from the secondary sources in the same fashion
• where wavefronts coincide (strong constructive interference), a new wavefront is formed
Huygens’ Wave Construction

- propagation from a point source

Christiaan Huygens (1629-1695)
Huygens’ Wave Construction

- reflection at a plane surface

Christiaan Huygens (1629-1695)
Huygens’ Wave Construction

- refraction at a plane surface

Christiaan Huygens (1629-1695)
A lovely example