Optical methods for enhanced light collection efficiency

Angelo Angelini
*Dipartimento di Scienze Applicate e Tecnologie (DISAT)*
*Politecnico di Torino*
Motivation

- In collision experiments an effective energy determination requires an efficient light collection.
- The energy resolution is affected by the light collection efficiency.
- In dosimetry sensitivity and limit of detection depend on the collection efficiency.
- High precision dosimeters are required in biomedical applications (radiotherapy, imaging).
Outline

- Introduction: visible light generation by charged particles or high energy photons
  - Cerenkov Effect
  - Scintillation

- How to deliver light to remote detectors
  - Total Internal Reflection based fibers
  - Photonic Crystal Fibers
  - Hollow Fibers

- Fiber-detector couplers
  - GRIN lenses, microlenses

- Controlling spontaneous emission with photonic nanostructures
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Visible light generation

High energy photons or particles may generate visible photons when interacting with matter

We focus on two distinct mechanisms:

- Cerenkov Effect
- Scintillation

UV-visible light: 2-5 eV
Cerenkov Radiation

A charged particle travelling faster than $c/n$ (speed of light in the medium) generates a coherent electromagnetic wave. The wavefront orientation depends on the particle speed:

$$\cos(\theta) = \frac{c}{n \cdot v}$$

Speed of the charged particle

The Cerenkov effect is an interference phenomenon -> intrinsically anisotropic
Scintillation

✓ Scintillation is a type of **luminescence**

✓ A **charged particle** or an **high energy photon** transfers its energy to the scintillator bringing it to an **excited state**

✓ The scintillator **re-emits radiation** in form of **lower energy photons** (typically UV or visible)

✓ The **material** has to be **transparent** to the emitted radiation

✓ The **absorption and emission** mechanisms depend on the nature of the scintillator:
  • **Organic scintillators** (liquid or solid)
  • **Inorganic scintillators**
  • **Gas scintillators**
Organic scintillators

✓ Absorption and emission depend on the energy levels of the **single molecule** (i.e. emission in nearly independent on the physical state)

✓ The energy separation between $S_0$ and $S_1$ is on the order of few eV (3-5 eV)

✓ The transitions from $S_3$ and $S_2$ to $S_1$ are **typically fast** (few ps) and **non-radiative**

✓ The excited electron **rapidly thermalize** to the $S_{10}$ state
Organic scintillators

Figure 1

Jablonski Energy Diagram

- Excitation (Absorption) 10^{-15} Seconds
- Internal Conversion and Vibrational Relaxation (10^{-14} - 10^{-11} Sec)
- Fluorescence (10^{-9} - 10^{-7} Sec)
- Intersystem Crossing
- Non-Radiative Relaxation
- Vibrational Energy States
- Delayed Fluorescence
- Intersystem Crossing
- Non-Radiative Relaxation (Triplet)
- Phosphorescence (10^{-3} - 10^{2} Sec)
- Excited Triplet State (T_1)

Ground State

Excited Singlet States

S_0

S_1

S_2
Organic scintillators

- $S_{e2}$: 10fs-10ps
- $S_{e1}$: 1ps-10ns
- $T_{e1}$: 100ns-1s
- $S_{e0}$: 1ps-100ps
Inorganic scintillators

✓ The scintillation mechanism depends on the **band structure of the crystal lattice**.

✓ In a pure crystal **electrons cannot occupy states within the forbidden band**.

✓ The decay of the electron to the valence band may generate a photon but **radiative decay is very inefficient!**
Inorganic Scintillators

- Moreover **typical band gaps in pure crystals are too high** to generate visible photons (auto-absorption!)

- The addition of impurities (activators) results in **trapping states within the band gap**

  - Lower energy photons
  - Reduced auto-absorption

The emissive properties (wavelength, decay rate, light yield) can be tuned by choosing the activators and the crystal
Inorganic Scintillators

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>BaF₂</th>
<th>BGO</th>
<th>LSO:Ce</th>
<th>GSO:Ce</th>
<th>YAP:Ce</th>
<th>LuAP:Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission peak (nm)</td>
<td>410</td>
<td>565/420</td>
<td>310/220</td>
<td>480</td>
<td>420</td>
<td>440</td>
<td>360</td>
<td>365</td>
</tr>
<tr>
<td>Light yield (ph/keV)</td>
<td>38</td>
<td>65</td>
<td>11/1.5</td>
<td>8.2</td>
<td>25</td>
<td>9</td>
<td>18</td>
<td>12</td>
</tr>
</tbody>
</table>

**Decay time**

<table>
<thead>
<tr>
<th></th>
<th>Slow (ns)</th>
<th>Fast (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>230</td>
<td>680/3000</td>
</tr>
</tbody>
</table>

| Density (g/cm³) | 3.7 | 4.5 | 4.9 | 7.1 | 7.4 | 6.7 | 5.4 | 8.4 |
| Chemical composition | Bi₄Ge₃O₁₂ | Lu₂SiO₅ | Gd₂SiO₅ | YAlO₃ | LuAlO₃ |

The total attenuation and absorption coefficients, $\mu$ and $\mu_{ph}$, respectively, were calculated with XCOM (Berger et al., 1999) without including the coherent scattering. The detector materials are: NaI(Tl) and CsI(Tl) — thallium-doped sodium/cesium iodide, respectively; BGO — bismuth germinate; LSO:Ce and GSO:Ce — cerium-doped lutetium/gadolinium oxyorthosilicate, respectively; YAP:Ce and LuAP:Ce — yttrium/lutetium aluminium perovskite, respectively.

The **emission peak** is typically at **shorter wavelength** with respect to organic scintillators.

The **decay rate** is typically **lower** (1 or 2 orders of magnitude) with respect to organic scintillators.
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  - Surface diffraction gratings
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  - Photonic Crystal Fibers

- Fiber-fiber and fiber-detector couplers
  - GRIN lenses, micro-lenses

- Controlling spontaneous emission with photonic nanostructures
How to deliver generated photons to the detector?

Light collection efficiency is a crucial parameter in scintillators.

An high light yield means:

- Higher resolution in energy determination
- Higher signal to noise ratio in biomedical imaging (lower radiation dose needed)
- Higher spatial resolution

Unfortunately photons in bulk scintillators are emitted in random directions and the major part of photons are lost
Total Internal Reflection (TIR)

Photons emitted below the critical angle are radiated outside the scintillator

Part of the photons are trapped within the scintillator by Total Internal Reflection (TIR)

Two distinct strategies:

We can enhance the extraction of photons from the material

We can enhance the confinement of photons within the scintillator (scintillating fibers)
Diffraction gratings

A periodic structure provides an additional momentum along the periodicity direction.

In the reciprocal space we can vectorially sum the wavevectors

$$ k_f = k_i \pm n \cdot G $$

$$ n = 0, \pm 1, \pm 2 \ldots $$
Light extraction from high refractive index materials

A surface corrugation can diffract the TIR light and extract it toward the detector


By this approach light yield has been improved by 46%
Scintillating Fibers

The alternative approach is to confine light within the high index material and guide it to the detector.

Scintillating fibers are well suited for:
- Dosimetry
- Neutron imaging
- Tracking detectors
- Calorimeters
- Cosmic ray telescopes
- Real time imaging systems
- Flow cells
Scintillating fibers in dosimetry and radiotherapy

A plastic multifiber scintillator dosimeter assures important advantages:

✓ real time measurement of 2D dose distribution
✓ high tissue equivalence (relevant in biomedical applications)
✓ a large dynamic range (100 keV – more than 20 MeV)
✓ no pressure and temperature dependence
✓ no high voltage near the probe
✓ small physical size
Scintillating fibers

A typical scintillating fiber device is composed by three elements:

![Diagram showing scintillator, fiber light guide, and PMT]

- \( \epsilon_{\text{accept}} \)
- \( \epsilon_{\text{couple1}} \)
- \( \epsilon_{\text{transmit}} \)
- \( \epsilon_{\text{couple2}} \)

The light coupling efficiency depends on the optical coupling of each component:

- Acceptance efficiency \( [\epsilon_{\text{accept}}] \)
- Coupling efficiency \( [\epsilon_{\text{couple}}] \)
- Transmission efficiency \( [\epsilon_{\text{transmit}}] \)

In a typical fiber based dosimeter:

\[
\epsilon_{\text{light}} = \epsilon_{\text{accept}} \epsilon_{\text{couple1}} \epsilon_{\text{transmit}} \epsilon_{\text{couple2}} = 0.02 \cdot 0.5 \cdot 0.8 \cdot 0.5 = 0.004
\]

Acceptance efficiency

It is the fraction of light produced in the scintillator travelling in the direction of the fiber bundle which would fall within the acceptance cone of the fiber.

\[
NA = \sqrt{n_{core}^2 - n_{clad}^2}
\]

In a typical plastic scintillation fiber \( \varepsilon_{\text{accept}} \approx 0.02 \)

In inorganic scintillating cores the value can be larger (larger \( n \)), but you have to consider the acceptance of the guiding fiber!
Transmission Fiber: Cerenkov Background Noise

Cerenkov Background Noise (CBN) is a crucial issue in dosimetry and specifically in radiotherapy.
In some conditions CBN can be even larger than the scintillation signal.
Cerenkov Background Noise in radiotherapy

In radiotherapy it is required an accurate determination of the radiation dose. Cerenkov light is highly dependent on the angle between the charged particle beam and the fiber axis.

The noise strongly depends on the specific experimental conditions.

Worst case! The sensor should be calibrated for each measurement!
How can we manage CBN?

**Self-reference system**

A secondary fiber without the scintillator adjacent to the signal fiber acts as ‘background fiber’

The Cerenkov light generated in the background fiber is assumed to be the same as in the signal fiber

**Main disadvantages:**

Does not work in high dose gradient experiments
Doubles the size and number of detectors needed
How can we manage CBN?

**Time-resolved substraction**
Cerenkov emission is a prompt process
Scintillation is a delayed process standing for longer time
The read-out can be performed after Cerenkov radiation terminates (temporal gating)

Disadvantages:
Inorganic scintillators with longer decay times are required
The initial scintillation signal is lost
A fast switching of the readout is required
Calibration applies to specific radiation pulse conditions
How can we manage CBN?

**Spectrally resolved subtraction**

Cerenkov intensity signal is proportional to $\lambda^{-3}$

By using a scintillator with long wavelength peak (>500 nm) the shorter wavelengths can be filtered out

Disadvantage

The method reduces the Cerenkov signal but does not removes it

Imposes a constrain on the scintillator emission spectrum
How can we manage CBN?

Remove the Cerenkov signal at its source
Air core fibers wold intrinsically remove the problem, since no Cerenkov signal is generated

Air core fibers can not work in TIR conditions. A different approach is required

Photonic Crystals for light confinement
Quantum Mechanics in a Periodic Potential (Crystal)

Periodicity of the lattice potential

\[ V(r) = V(r + R) \]

Electromagnetism in a Periodic Dielectric (Photonic Crystal)

Periodicity of the dielectric constant

\[ \varepsilon(r) = \varepsilon(r + R) \]

Dispersion diagram of electron energy

\[ E = E(k) \]

Dispersion diagram of photon frequency (energy)

\[ w = w(k) \]
For wavelength in band gap

\[ \lambda_{m}/2 = a \quad k = \pi/a \]

For wavelength not in band gap

1 INCIDENT WAVE
2 REFLECTED WAVES IN PHASE
3 TOTAL WAVE

1 INCIDENT WAVE
2 REFLECTED WAVES NOT IN PHASE
3 TOTAL WAVE
Distributed Bragg Reflectors

layer numbers

spectrum sharpness

reflectance within stop band

- 8 periods
- 6 periods
- 4 periods
- 2 periods

energy [eV]

Reflectance

energy [eV]
Distributed Bragg Reflectors

refractive index contrast

stop band width

\begin{align*}
  n_1 &= 4.5 \quad n_2 = 1.7 \\
  n_1 &= 4.0 \quad n_2 = 1.7 \\
  n_1 &= 3.5 \quad n_2 = 1.7 \\
  n_1 &= 3.0 \quad n_2 = 1.7
\end{align*}

\textbf{Reflectance}

\textbf{energy [eV]}

\textbf{energy [eV]}
Distributed Bragg Reflectors

Transmittance vs. frequency (arb. units)

Stop band
Defects in the DBR

Defect state in the gap

Transmittance

frequency (arb. units)

Stop band

$\varepsilon_1$

$\varepsilon_2$

$\varepsilon_3$
Band diagram for a triangular lattice of air column drilled in a dielectric medium with $\varepsilon = 12$ (Silicon)

Filling fraction

$r/a = 0.48$
2D Photonic Crystals

- Electric field
- Photonic Band Gap
- Frequency (ω/2πc)
- TE modes
- TM modes
- Reflection
- Wavelength
- Γ-M
- Γ-K
2D Photonic Crystals

\[ \frac{r}{a} = 0.48 \]

\[ \frac{\omega a}{2\pi c} = \frac{a}{\lambda} \]

\( a = 675 \text{ nm}, \quad r = 324 \text{ nm} \)

phot gap center at \( \lambda = 1.5 \mu\text{m} \)

\( a = 13.5 \text{ mm}, \quad r = 6.5 \text{ mm} \)

phot gap center at \( l = 3 \text{ cm} \)

\( n = 10 \text{ GHz} \)
Defects in 2D Photonic Crystals

Without defects
Point defect
\textit{resonant cavity}
line defect
\textit{waveguide}
2D Photonic Crystal waveguides

Photonic Crystal waveguides allows for very tight bends
Guided modes in Photonic-Crystal waveguide as seen by a SNOM
Corner PC membrane: 14x14 μm² scan area

\( \lambda = 1550.00 \text{ nm} \)
Photonic Crystal Fibers

Conventional fibre

- Total internal reflection

Photonic crystal fibre

- Total internal reflection by the effective refractive index of the cladding region.

invented by P. Russel et al. in 1996 at Univ. of Southampton, UK
PC Fibers can operate:

i) through standard index guiding (higher refractive index of the core region vs. the cladding)

ii) through photonic bandgap effects of the patterned cladding vs. the core region (defect)

Possible air-guiding configurations
Photonic Crystal Fibers: Applications

- Dosimetry
- Fiber optics communication
- Fibre lasers
- Nonlinear devices
- High-power transmission
- Highly sensitive gas sensors
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Fibers Coupling: Graded Index (GRIN) Lenses

GRIN lens allows to shape the beam profile to optimize the optical coupling between two different fibers.
Fibers Coupling: Graded Index (GRIN) Lenses
Fiber couplers

Part of the photons can be lost at the fiber-fiber interface

In some applications small sensors are required (better integration, lower noise, lower power consumption)

The sensor size can be smaller than the light spot
A Fresnel lens largely reduces the volume of the lens
Fabrication of optical elements on fiber facets

Focused Ion Beam Lithography

Two-photon lithography
Fiber couplers

With Focused Ion Beam Lithography and two photon lithography it is possible to fabricate optical components directly on the fiber tip.
Polymeric Couplers for fiber bundles


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Spontaneous emission control: Purcell Effect

A photonic crystal structure modifies the Local Density of Optical States (LDOS)

Local Density of States counts for the number of states at a given frequency and location (similar to electronic density of states)

The emissive properties of an emitter can be modified according to the Fermi Golden Rule:

$$\gamma_R(\mathbf{r}, \omega, \mathbf{d}) = \frac{\pi \omega}{\hbar \epsilon_0} |\langle \Psi_f | d | \Psi_i \rangle|^2 \rho(\mathbf{r}, \omega, \mathbf{d})$$

- Decay Rate
- Transition Probability
- LDOS
Purcell effect

2D Photonic Crystal (In-plane bandgap)

When PBG spectral position matches the emission, the decay rate is reduced and out of plane emission is enhanced.

Purcell effect

In high quality microcavities or defect states within the photonic crystal bandgap the LDOS can be greatly enhanced for resonant wavelengths.

Conclusions

✓ Depending on the experimental conditions, some optical methods can be implemented to increase the light collection efficiency

✓ By means of photonic micro and nanostructures it is possible to guide, confine or concentrate light

✓ Photonic structure offer a chance to control the spontaneous emission and engineer the radiative decay process
Thanks for your kind attention!

Contacts:
Prof. E. Descrovi  emiliano.descrovi@polito.it
Dr. A. Angelini   angelo.angelini@polito.it
Optical antennas for light concentration

Perchè detector piccoli (riduzione noise)
Focusing and beam shaping assisted by Surface Plasmons
Focusing and beam shaping assisted by Surface Plasmons: grating couplers
Focusing and beam shaping assisted by Surface Plasmons