Improved Light Extraction Efficiency on 2 inches LYSO with Nanopatterned TiO_2 Photonic Crystals

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Improving PET images through photonic solutions: the Turbo-PET project

Problematic

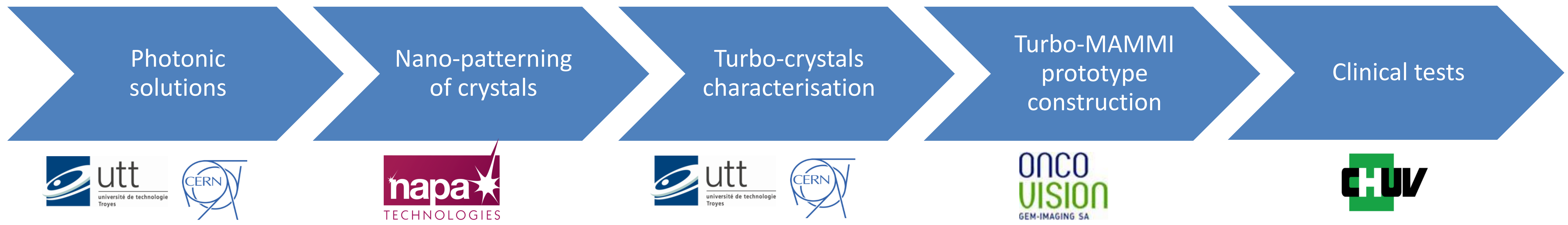
- In a PET scanner detector, the high refractive index of the scintillator crystal causes a large number of the produced UV-vis photons to remain trapped inside the crystal: therefore up to the 70% of the light produced is not collected by the photodetector.
- The spatial resolution and the sensitivity of existing PET systems suffer from this low collection efficiency of photons.

Solution

- Light extracting layers can be deposited/fabricated on the exit surface of the scintillator crystal in order to increase the number of photons extracted.
- A possible light extraction layer is a nano-patterned thin film of a material with refractive index higher than the LYSO scintillator (n > 1,8): this diffraction grating is referred to as 'photonic crystal' (PhC) (*Fig.2* and *Fig.3*) [1].

In order to demonstrate the benefits of photonic crystals for PET imaging, the partners of the Turbo-PET project are committed to the development of a new high-resolution, high-sensitivity nuclear imaging breast PET system.
CERN and UTT develop and simulate light extracting photonic solutions. NAPA patterns the LYSO scintillating crystals blocks (Turbo-crystals) that will be inserted in the MAMMI breast-imaging PET scanner already commercialized by ONCOVISION [2]. A Turbo-MAMMI prototype will be installed early 2017 at CHUV in Lausanne for clinical tests. The prototype holds two rings each with 12 scintillator + PMT modules: one ring will be equipped with nano-patterned crystals, the other ring will not be modified. The comparison of PET images taken from each ring will demonstrate the added performance in terms of resolution and sensitivity.

Fig. 1



The UV-vis photons impinging the exit surface beyond the critical angle of total internal reflection (TIR) out-diffract thanks to the diffraction grating coated on the monolithic scintillator. This results in improved light extraction efficiency.

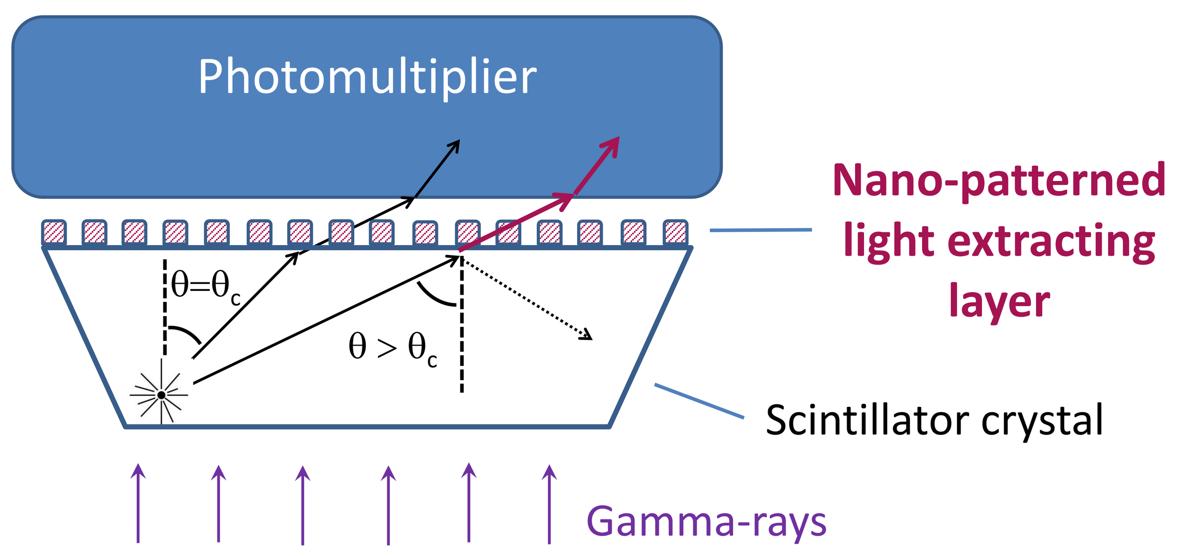


Fig. 2 PET-scan detector: scheme of the physical principle of light extraction from the scintillator crystal to the photomultiplier (PMT).

The key challenge is large scale homogeneous nano-patterning. This 5x5 cm area nano-patterning of the TiO_2 layer was realized by nano-imprint lithography techniques [3].
Pattern parameters: square lattice, period = 630 nm, diameter = 570 nm, height = 300 nm

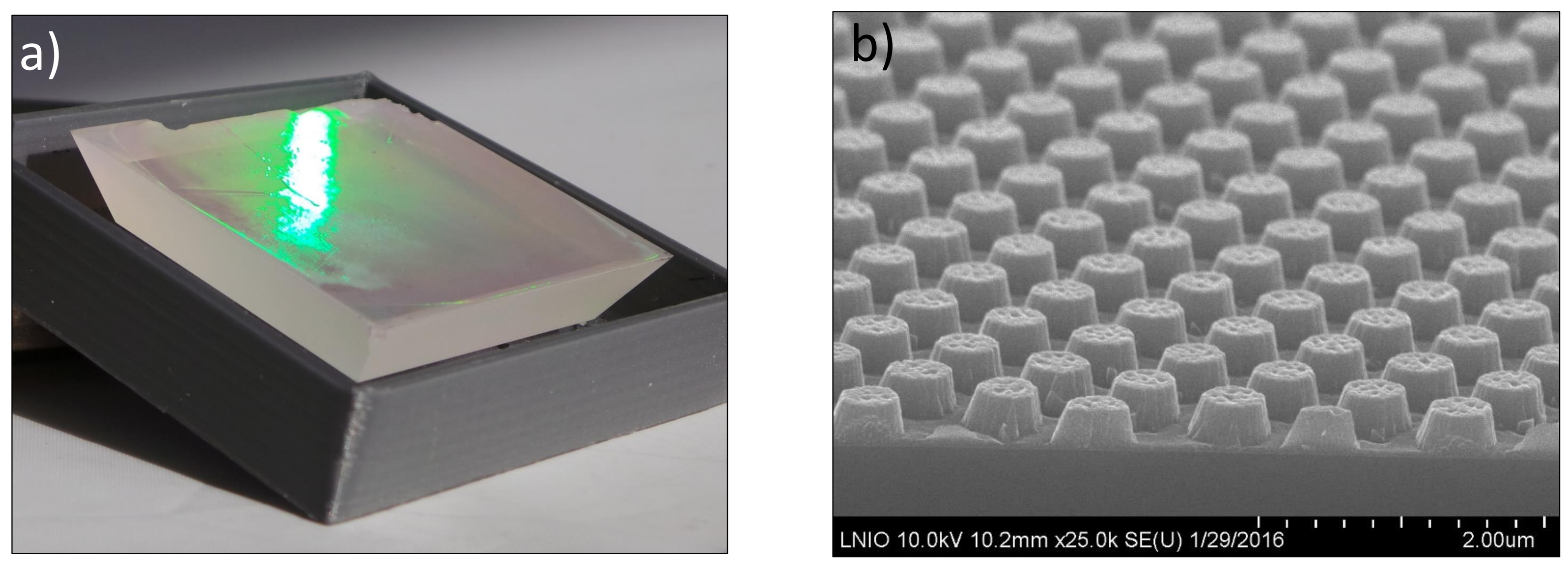


Fig. 3 a) LYSO monolithic scintillator covered with a two-dimensional TiO_2 (n ≈ 2,4 at λ = 420 nm) photonic crystal pattern on its 5x5 cm exit face; b): SEM images of the TiO_2 pillars.

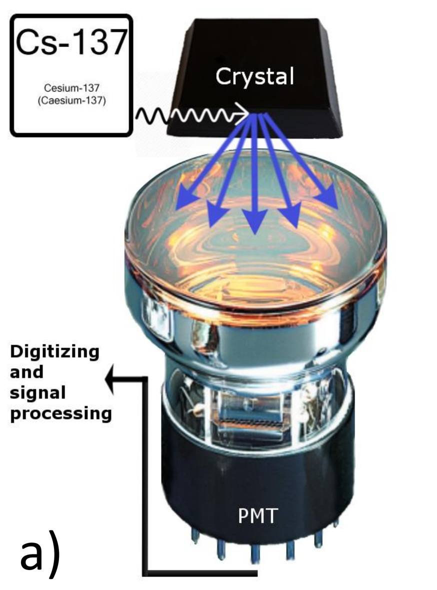
Characterizations set-ups and results

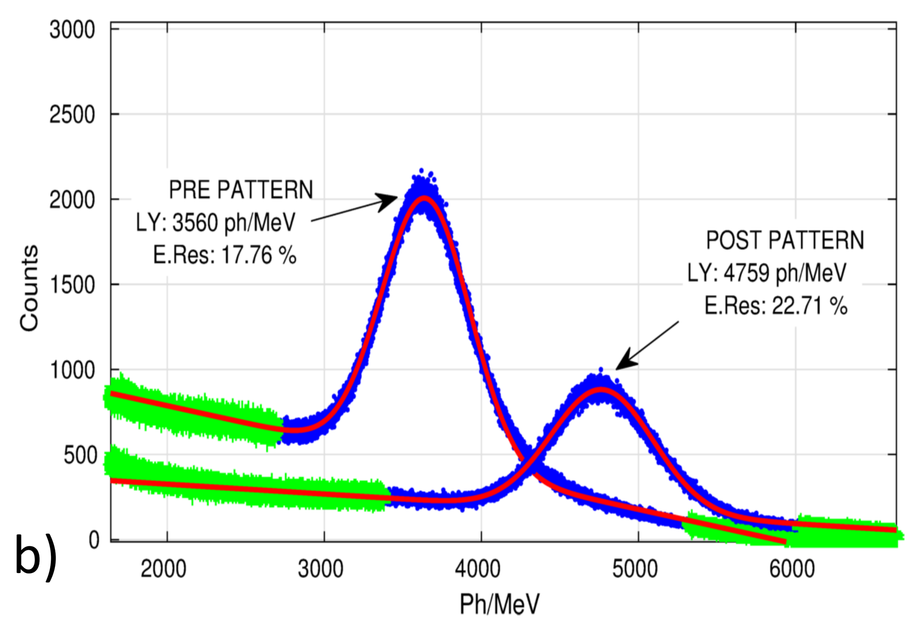
The improvement in light extraction efficiency of the photonic crystal coated scintillator LYSO crystals has been measured by **light yield measurements with a Cs^{137} radioactive source (a,b,c)** at CERN and optically, by **laser-excited photoluminescence (d,e,f)** at ICD/LNIO, CNRS - Université de Technologie de Troyes.

a) *Large area PMT is used to detect light exiting the read out face of an LYSO crystal (Fig. 3a), excited with Cs-137 source. The output signal of the PMT is then digitized.*

b) *The digitized signal is analyzed and the light yield between the pre- and post-patterning characterization are compared:*

$$gain = \frac{Extr.efficiency\ with\ PhC\ coating}{Extr.efficiency\ without\ PhC_g}.$$

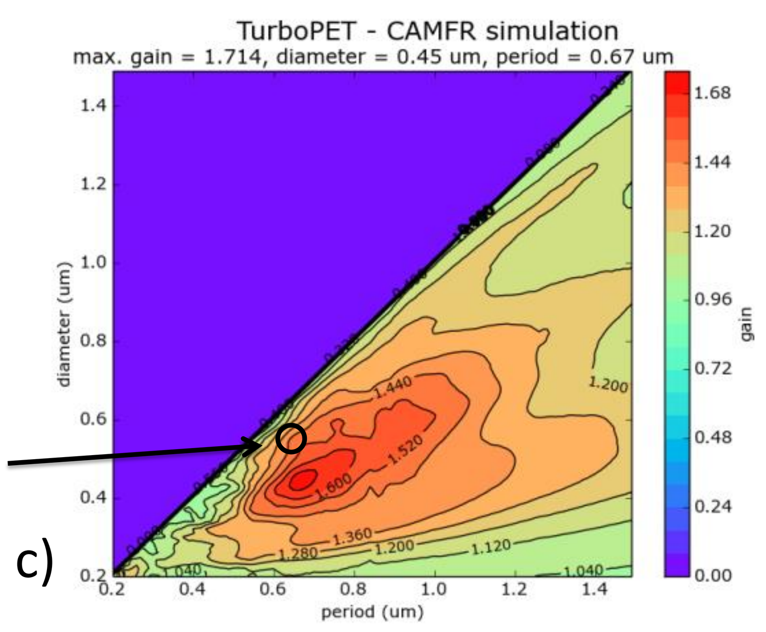




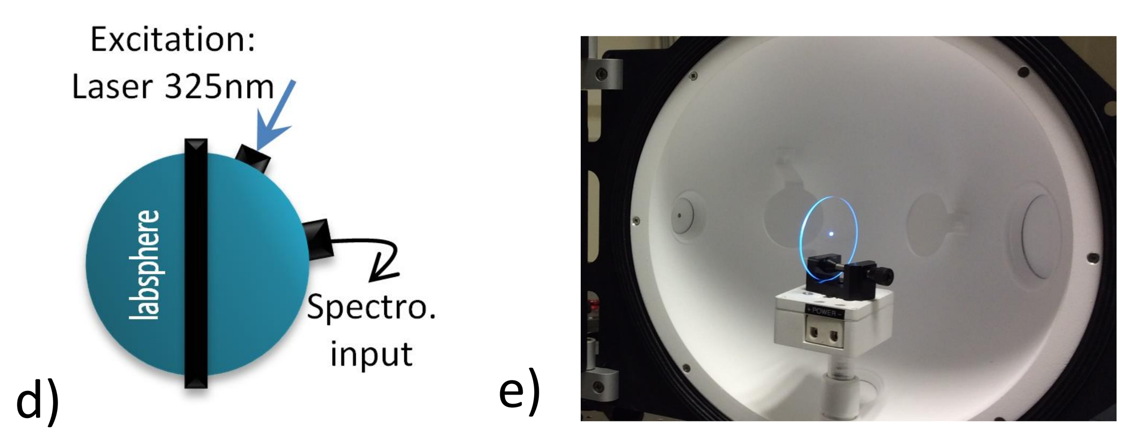
Light output gain

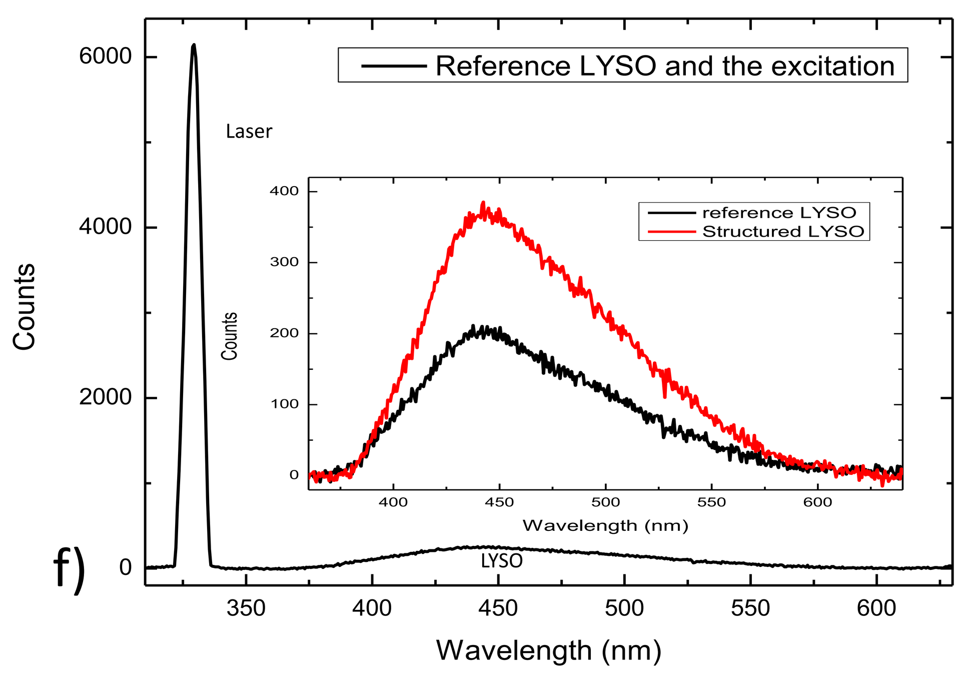
$$\frac{4759\ ph/MeV}{3560\ ph/MeV} \rightarrow +34\ \%$$

c) The experimental light output gain is consistent with the simulation of realized pattern, i.e. *43 %*



d) *Laser-excited photoluminescence set-up.*
e) *Nano-patterned LYSO crystal wafer inside the integrating sphere. Laser-excited PL will allow measurement of light output faster than nuclear characterization.*





Light output gain

$$EQE_{sample} = EQE_{ref} + 100\%$$

$$EQE = \frac{S_3^{PL}}{S_1^{Laser}}$$

S_3^{PL} *: LYSO PL at direct excitation*
S_1^{Laser} *: Excitation without LYSO in the sphere*

f) *Spectrum of light collected: the laser excitation at λ = 325 nm and the LYSO photoluminescence are visible; in the inset the pre- and post-patterning LYSO light output are compared: the periodic array of TiO_2 nano-pillars doubles the external quantum efficiency (EQE, number of photons exiting the LYSO crystal).*

Conclusions: both nuclear and optical characterization methods demonstrate an improvement of the LYSO light output given by the photonic crystal. Nano-imprint makes possible the nano-patterning over large areas at a lower cost than other lithography techniques.

[1] A. Knapitsch and P. Lecoq, "Review on photonic crystal coatings for scintillators," *Int. J. Mod. Phys. A*, vol. 29, no. 30, p. 1430070, Nov. 2014.
[2] http://oncovision.com/content/mammi.
[3] C.-C. Yu and H.-L. Chen, "Nanoimprint technology for patterning functional materials and its applications," *Microelectron. Eng.*, vol. 132, pp. 98–119, Jan. 2015.

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