부산대학교
PUSAN NATIONAL UNIVERSITY

RADIATION IMAGING LABORATORY

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Design of $CdWO_4$-photodiode detector for x-ray container inspection system focusing on optical characteristics

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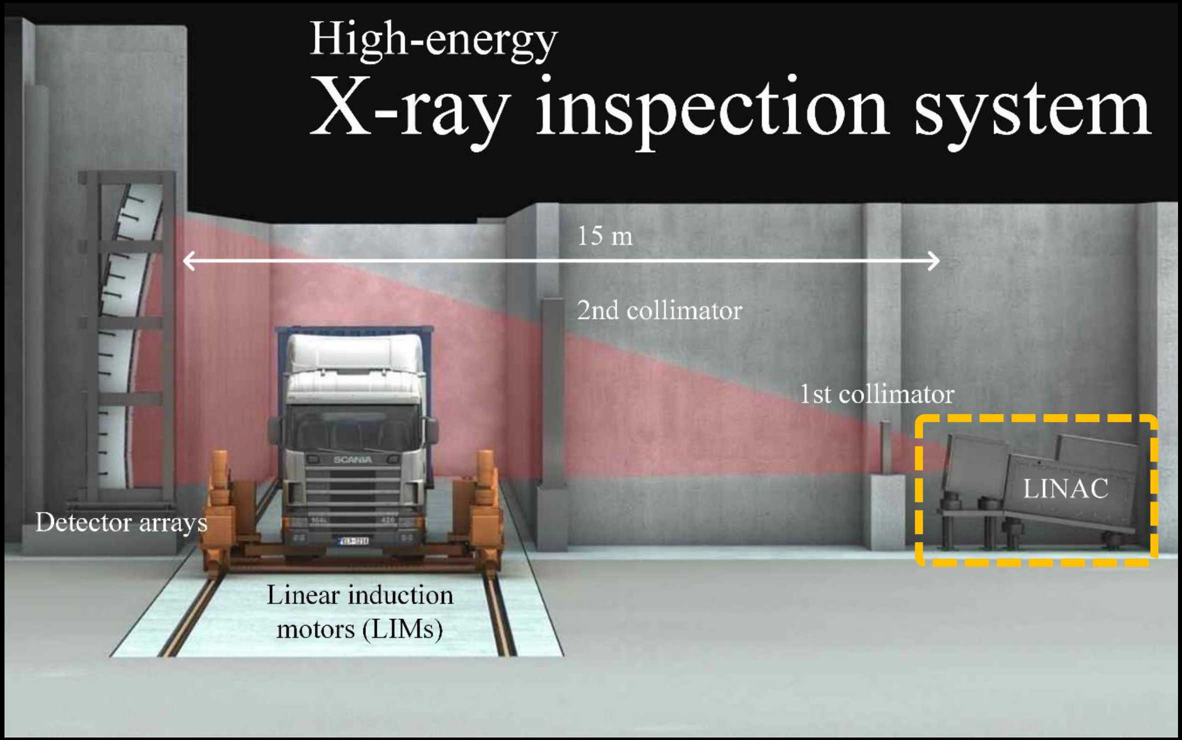
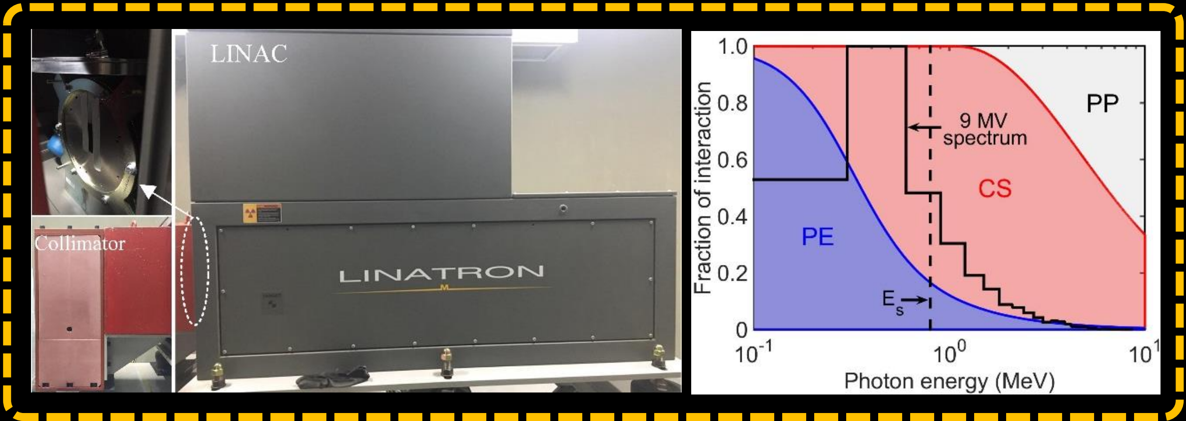
Container inspection system

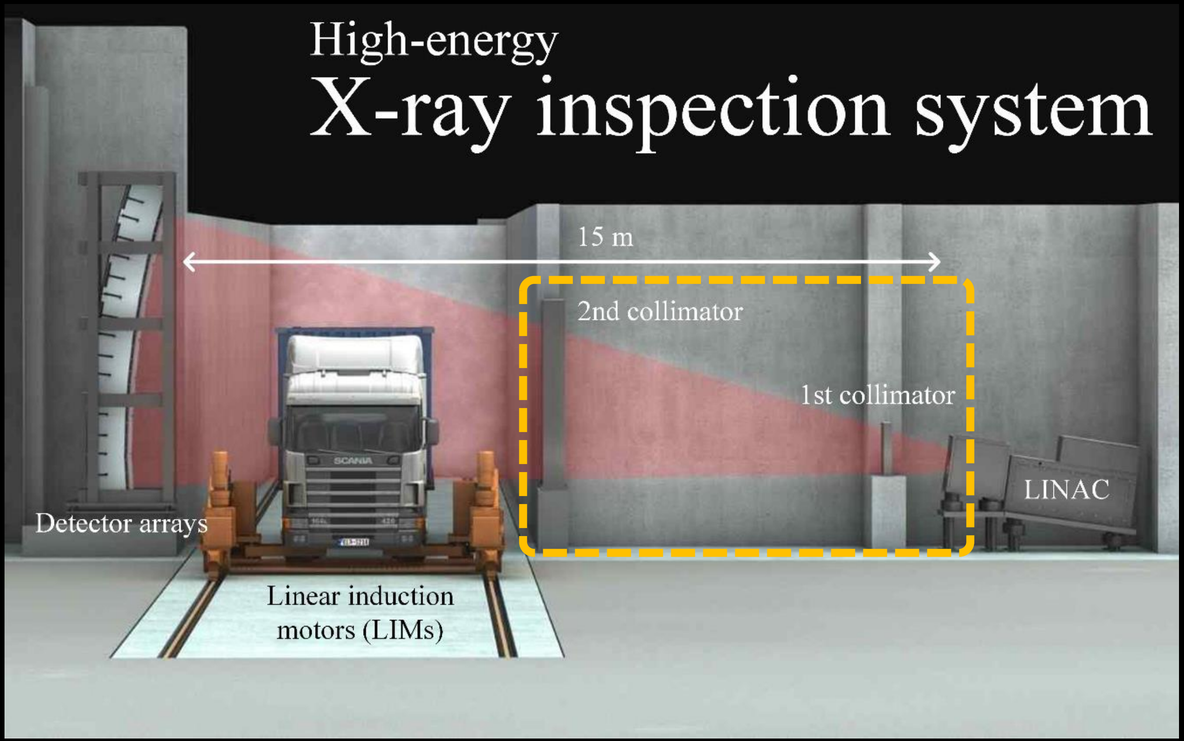
- To inspect cargo-container, high-energy x-ray inspection systems are mostly used
- Linear accelerator (LINAC) generates high-energy x-ray
- 6, 9 MV energy is typically used for inspection
- At 9 MV x-ray spectrum, compton scattering is dominant
- Mean energy of 9 MV spectrum is about 0.8 MeV

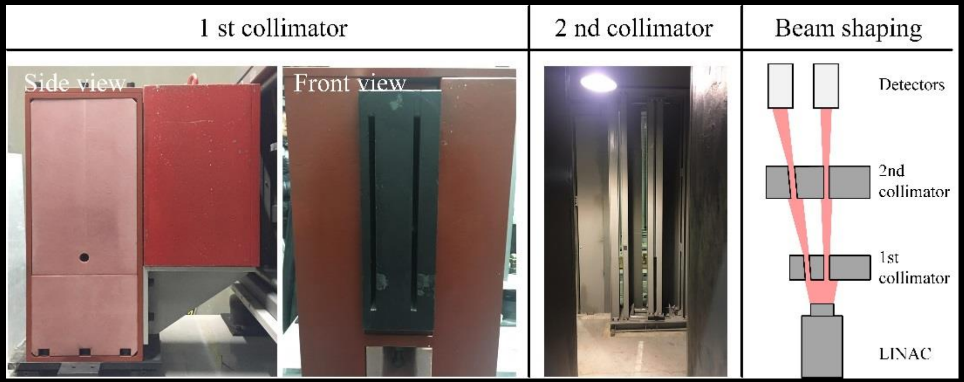




Container inspection system

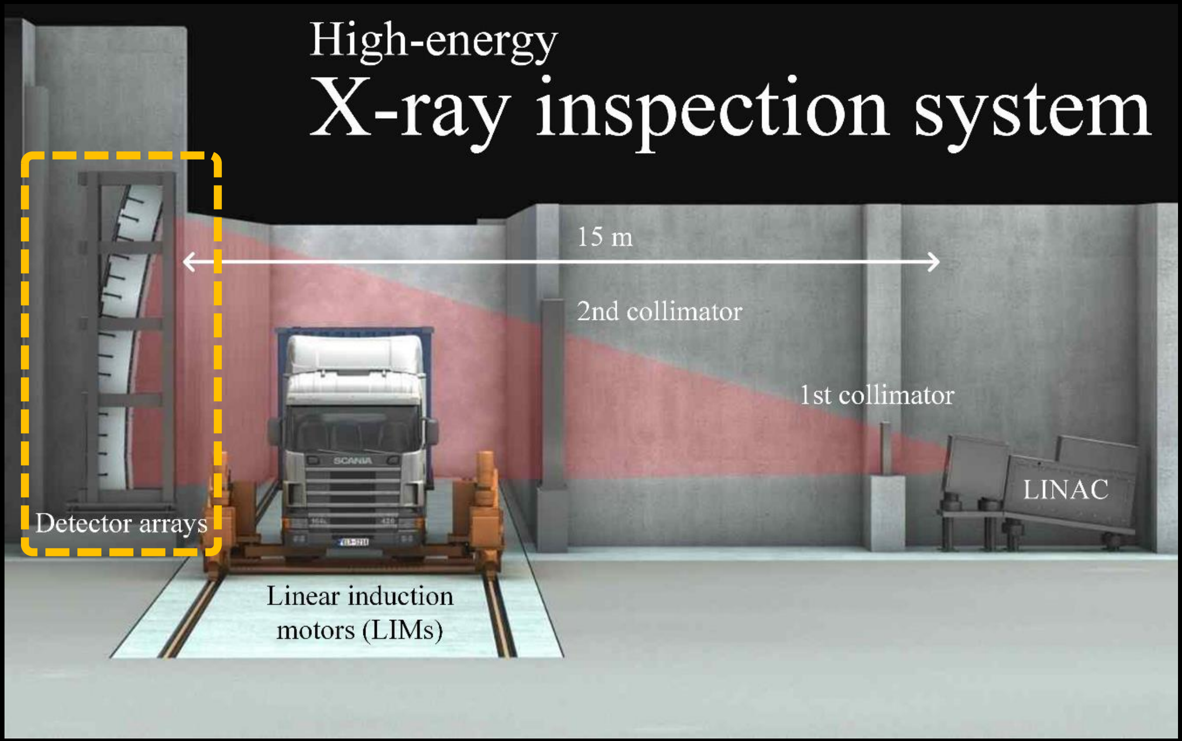
- X-ray beam is collimated by two collimators
- Collimator reduces the scatter due to unnecessary exposure
- X-ray beam shaped by collimators enter the linear detector arrays



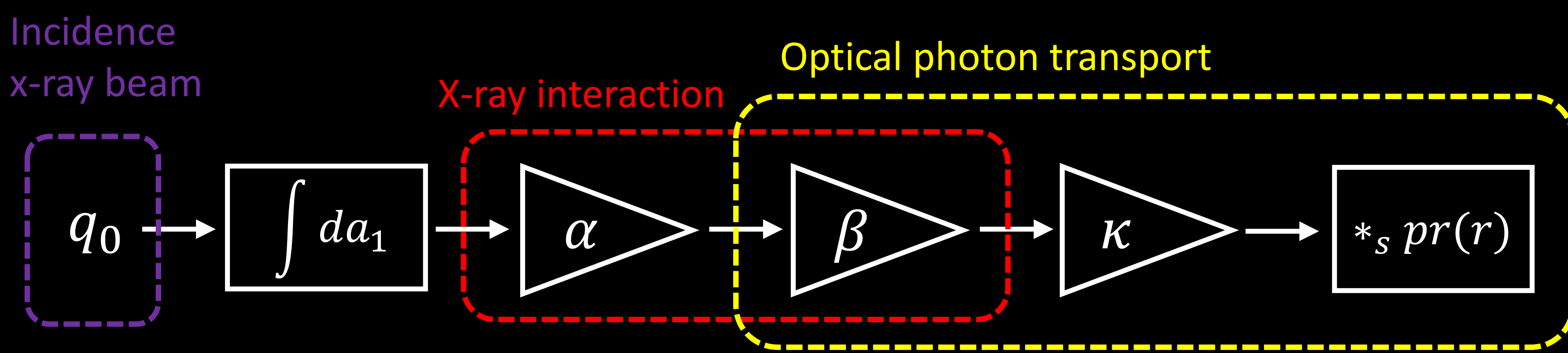


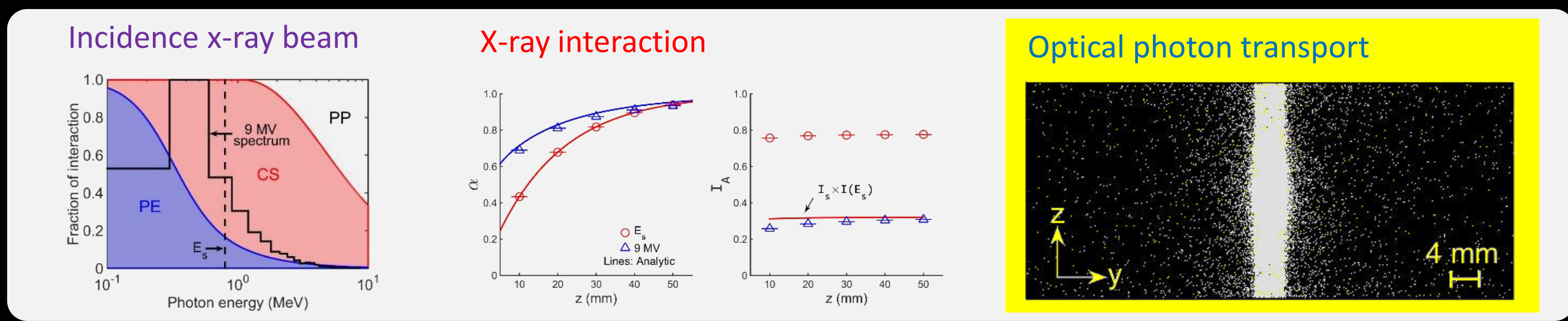
Container inspection system

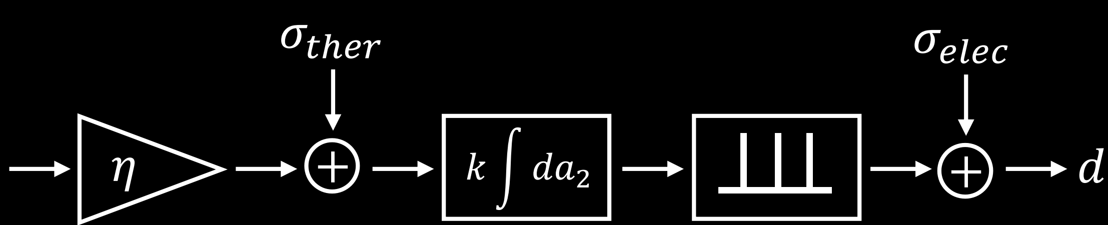
- In container inspection system, linear detector arrays are used
- Each module has 32-channels scintillator-photodiode coupled structure, and linear detector arrays are constructed by 32 modules
- To avoid radiation damage, the photodiode arrays, which detect the optical photons emitted from the scintillator arrays, are placed to the sides of detector arrays



System modeling

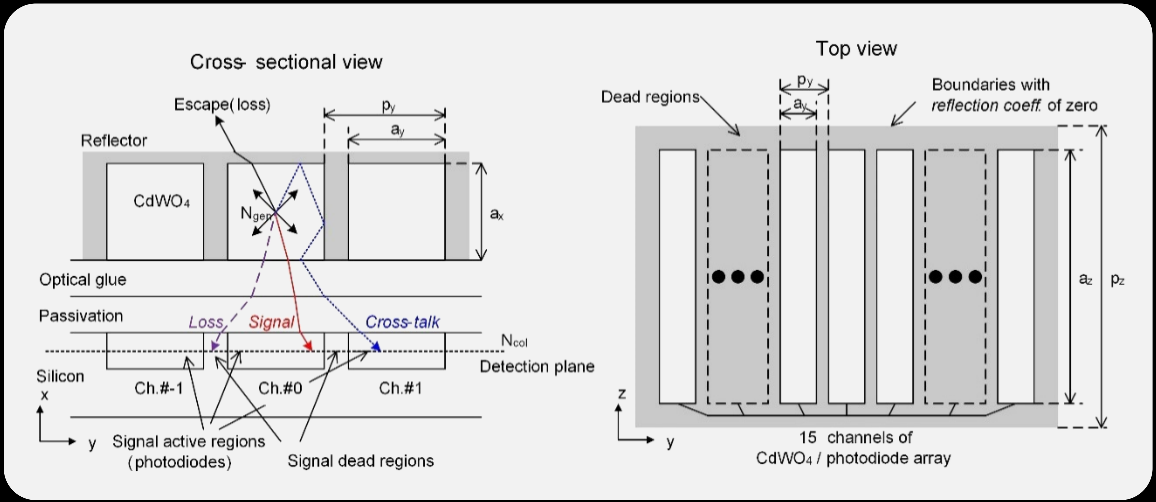






Optical photon transport

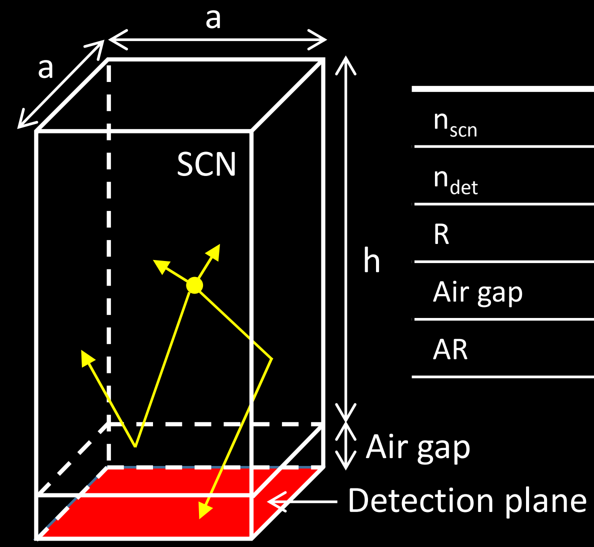
- Transport of optical photons is simulated by using an Monte Carlo (MC) simulation model, so called DETECT2000
- Detector geometry designed for MC simulation, and the $CdWO_4$/photodiode linear array consists of 15 channels
- Three cases of N_{col} quanta, such as signal, cross-talk, loss, at the detection plane are illustrated



	Material	Refractive index (n)	Reflection coefficient (R)	Thickness
Scintillator	$CdWO_4$	2.3	-	$4 \times 4 \times 30\ mm^3$ $(a_x \times a_y \times a_z)$ $4.6 \times 15.6\ mm^2$ $(p_y \times p_z)$
Optical glue	-	1.5 (1.0-4.4)	-	100 μm (10-1000)
Passivation layer	Si_3N_4	2.0 (1.0-4.4)	-	100 nm (10-1000)
Photodiode	Si	4.4	-	1 μm
Reflector	Al foil	2.5	0.79	100 μm
	TiO_2	2.5	0.96	
	Teflon	1.4	0.99	

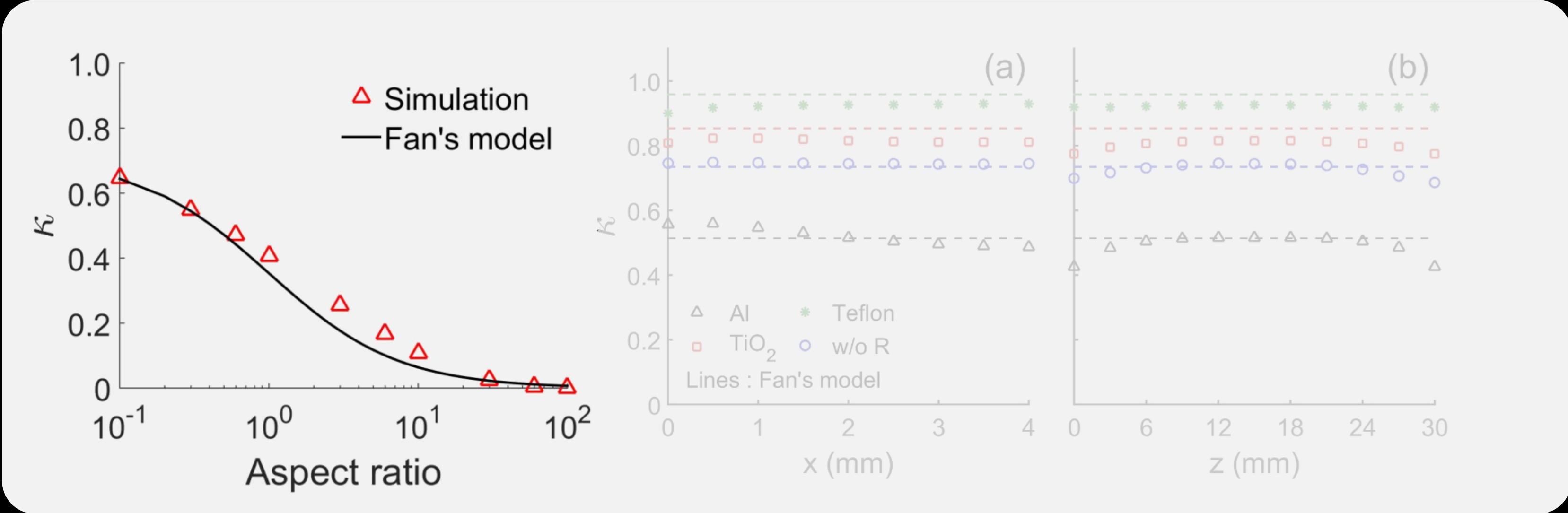
Verification

- $\kappa = \tau a_{geo}\left[\frac{1}{1-R(1-\tau a_{geo})}\right]$
  - $a_{geo} = {}^{a_{active}}/_{a_{total}}$
  - a_{active} and a_{total} refer to, respectively, the total surface area and the surface area of the portion of the scintillator to which the photodiode is coupled
  - R is the surface reflection coefficient
  - τ represents the probability that a photon impinging on a_{active} is absorbed by the photodiode



n_{scn}	2.3
n_{det}	1
R	0.7
Air gap	1 μm
AR	$10^{-1} – 10^{2}$

AR = a / h



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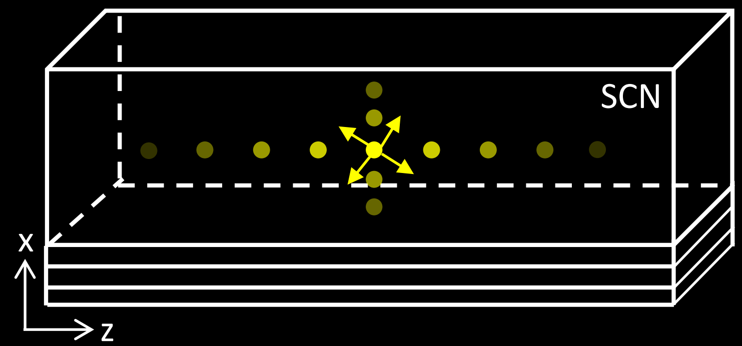
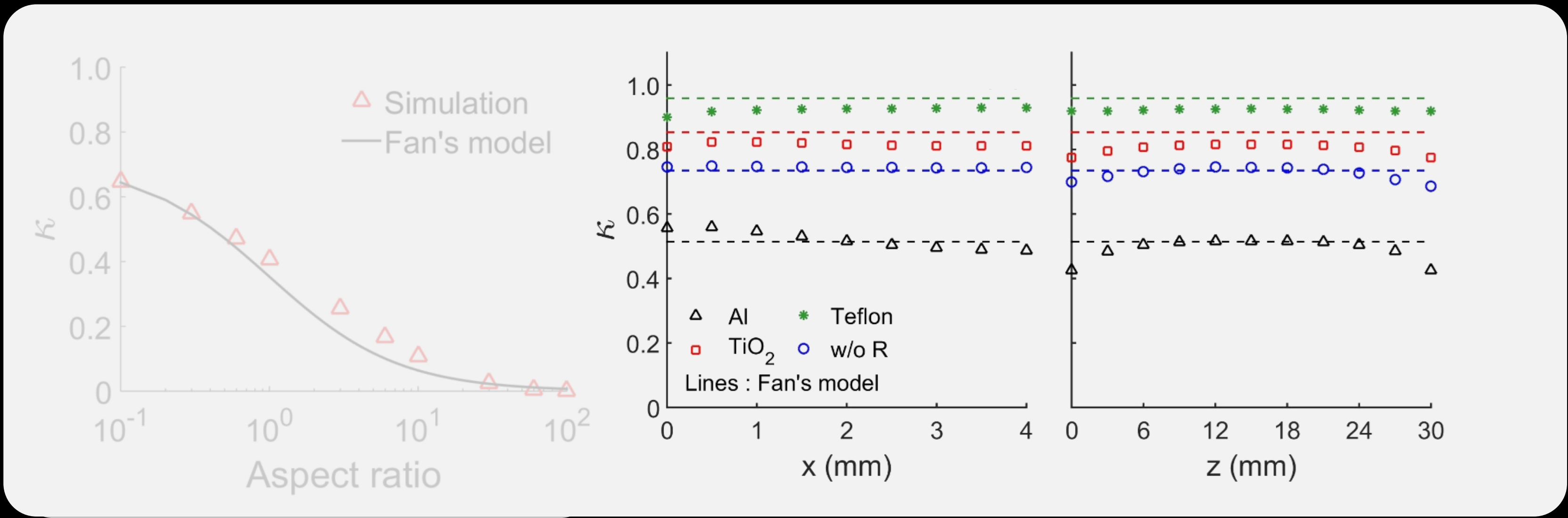
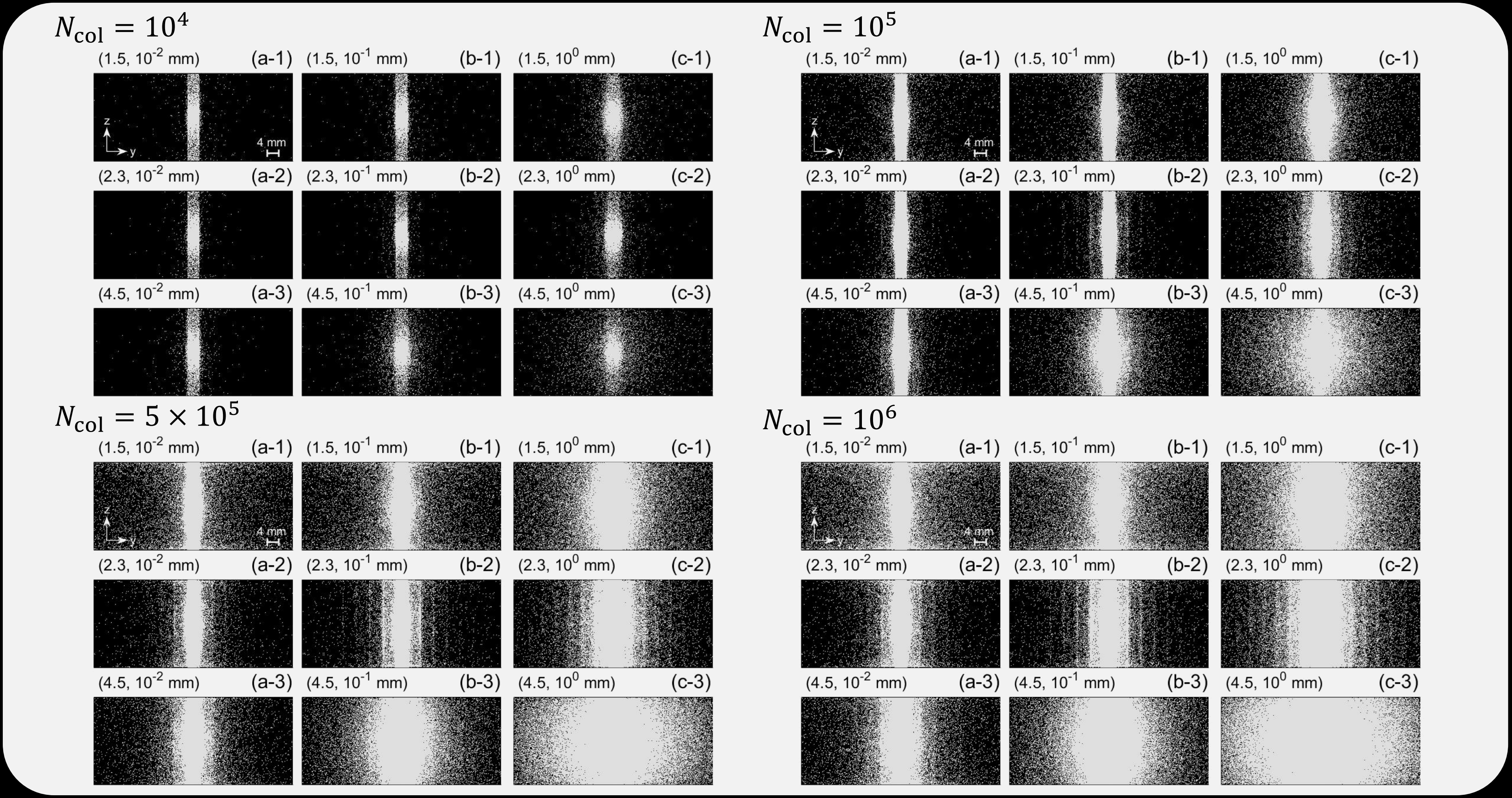


Scintillator	Optical glue	Passivation	Photodiode	Note
n_{scn}=2.3 4 x 4 x 30 mm^3	n_{opt} = 2.3 t_{opt} = 100 µm	n_{pass} = 2.3 t_{pass} = 100 nm	n_{pd} = 2.3 t_{pd} = 1 µm	15 ch.



Quantum image

- $q(y,z) = q(\mathbf{r}) = \sum_{i=1}^{N_{\mathrm{col}}} \delta(\mathbf{r} - \mathbf{r}_i)$ with $\int_z \int_y q(y,z)\mathrm{d}y\mathrm{d}z = N_{\mathrm{col}}$



Analysis of quantum image

- Because $q(y,z)$ has negligible spatial extent, to realize the spatial distribution we may sum the number of vectors within a small y-space bin Δy:
  - $c(y_j,z) = \int_{y_j-\Delta y/2}^{y_j+\Delta y/2} q(y,z)\mathrm{d}y$

- Then, an line-spread function (LSF) is given by
  - $L(y_j) = \int_{-p_z/2}^{p_z/2} c(y_j,z)\mathrm{d}z$

- The number of optical quanta collected at the mth photodiode channel is given by
  - $c_m = \int_{-\infty}^{\infty} L(y_j) \prod\left(\frac{y_j - m p_y}{a_y}\right) \mathrm{d}y_j \; ; \quad m = 0, \pm 1, \ldots \pm 7$

- The number of optical quanta arriving at the nth "dead region" is given by
  - $l_n = \int_{-\infty}^{\infty} L(y_j) \prod\left(\frac{y_j - n p_y + p_y/2}{p_y - a_y}\right) \mathrm{d}y_j \; ; n = \pm 1, \ldots \pm 7$

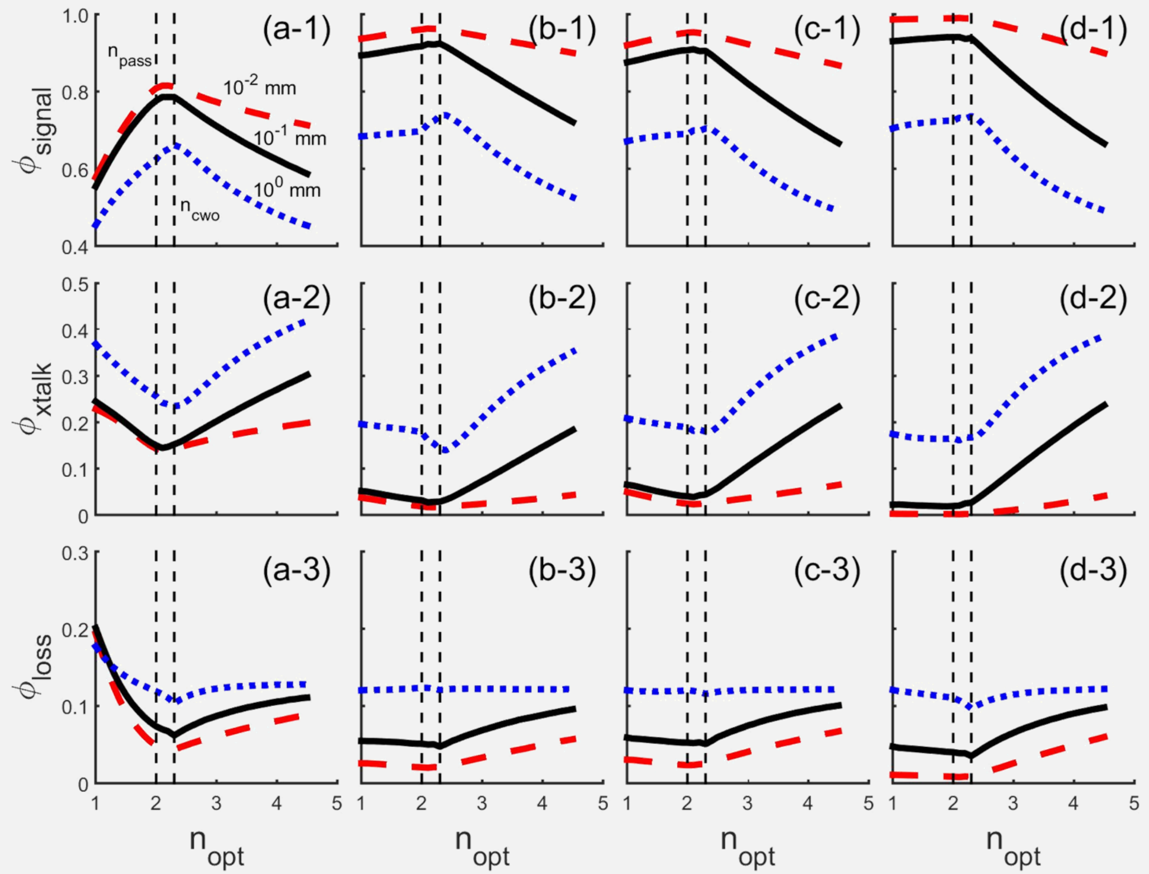
Analysis of quantum image

- The "light collection efficiency (LCE)" is defined as
  - $\kappa = \frac{N_{\mathrm{col}}}{N_{\mathrm{gen}}} = \kappa(\phi_{\mathrm{sig}} + \phi_{\mathrm{xtalk}} + \phi_{\mathrm{loss}})$
    - $\phi_{\mathrm{sig}} = \frac{c_0}{N_{\mathrm{col}}}$
    - $\phi_{\mathrm{xtalk}} = \frac{\sum_{m=1}^{7} c_{\pm m}}{N_{\mathrm{col}}} = \phi_{\mathrm{sig}} \sum_{m=1}^{7} f_{\mathrm{xtalk}}(\pm m) = \frac{c_{\mathrm{xtalk}}}{N_{\mathrm{col}}}$
    - $\phi_{\mathrm{loss}} = \frac{\sum_{n=1}^{7} l_{\pm n}}{N_{col}} = \phi_{\mathrm{sig}} \sum_{n=1}^{7} f_{\mathrm{loss}}(\pm n) = \frac{l_{\mathrm{loss}}}{N_{\mathrm{col}}}$

- It would be the most concern that how many optical quanta are collected at the $zero$th photodiode channel for the N_{gen} quanta within the $zero$th scintillator in the detector array. This figure of merit is given by
  - $\mathrm{FOM} \equiv \frac{c_0}{N_{\mathrm{gen}}} = \kappa\phi_{\mathrm{sig}}$

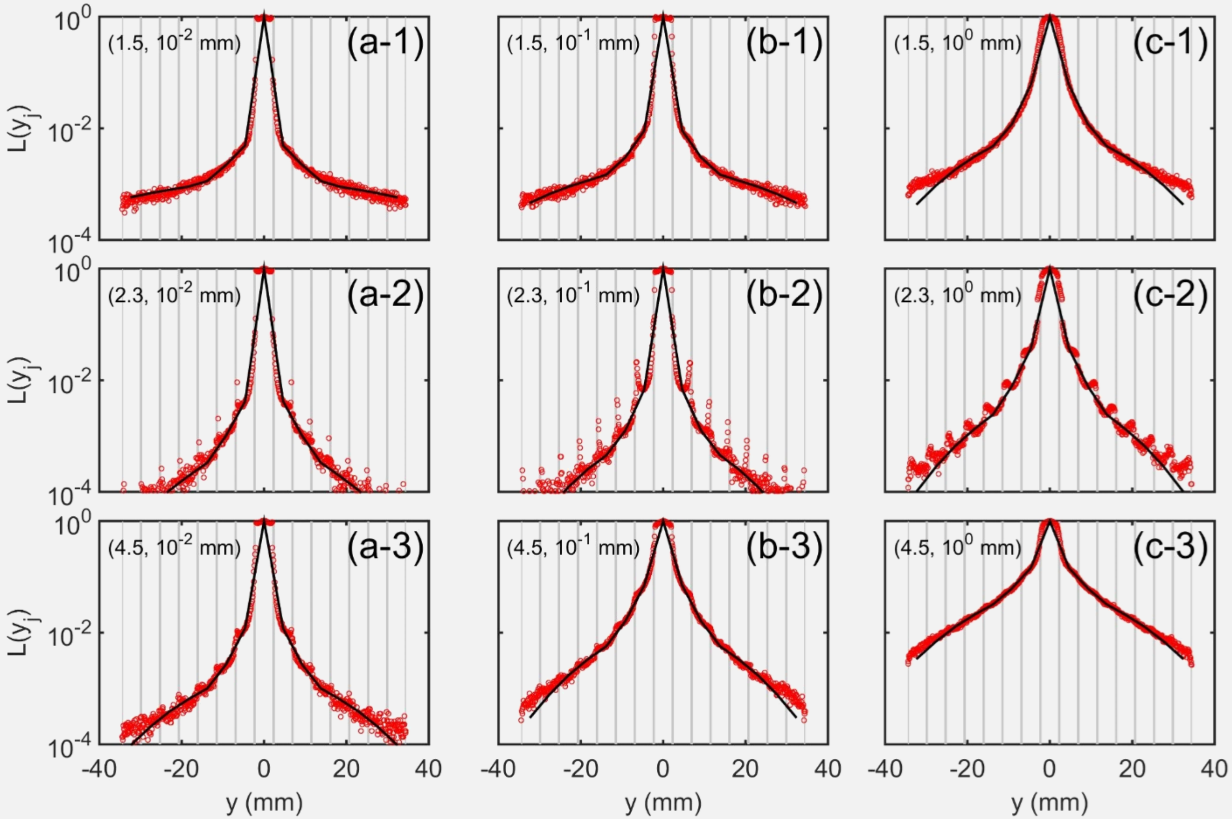
Results for the varying properties of optical glue

- Quantum distribution



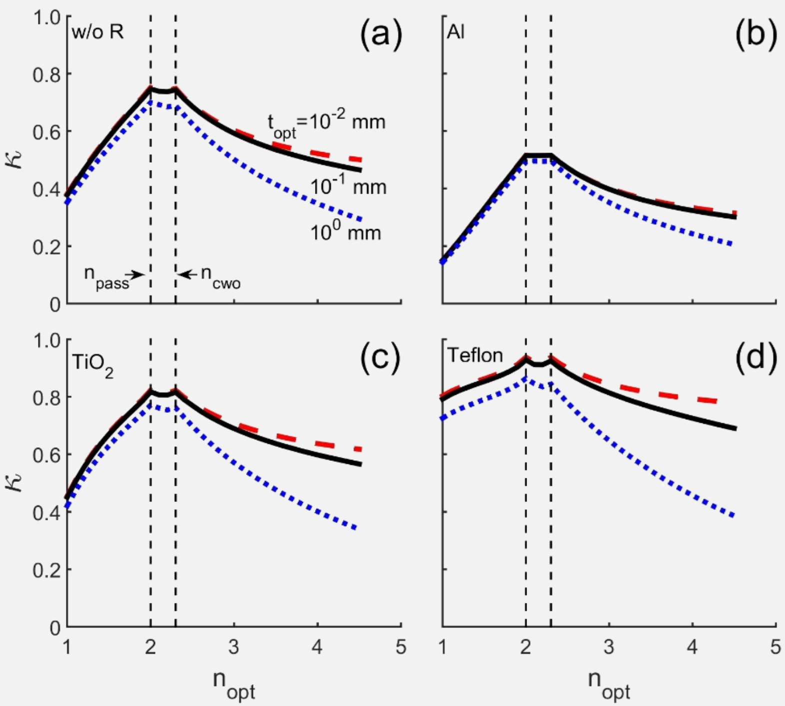
Results for the varying properties of optical glue

- Line-spread function

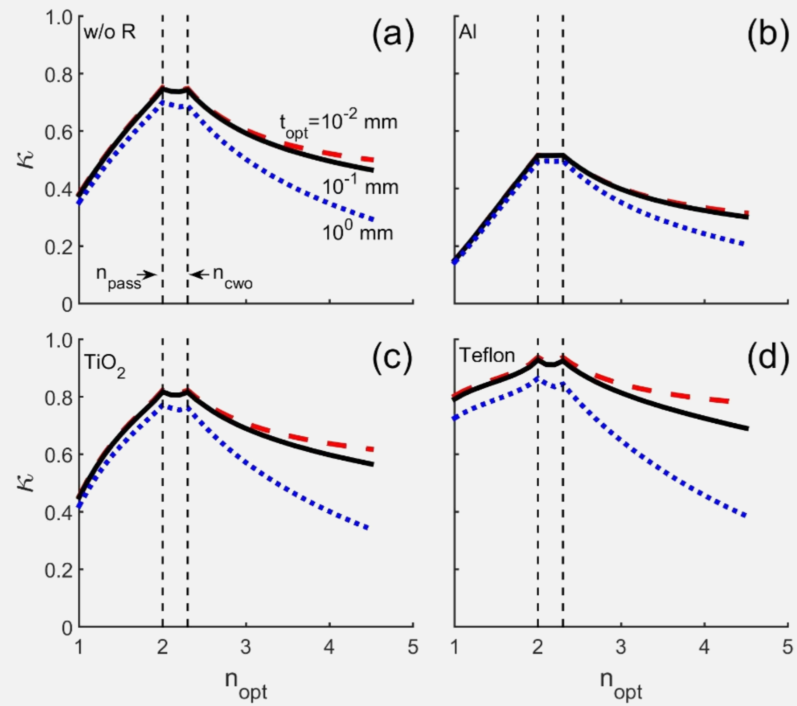


Results for the varying properties of optical glue

- LCE

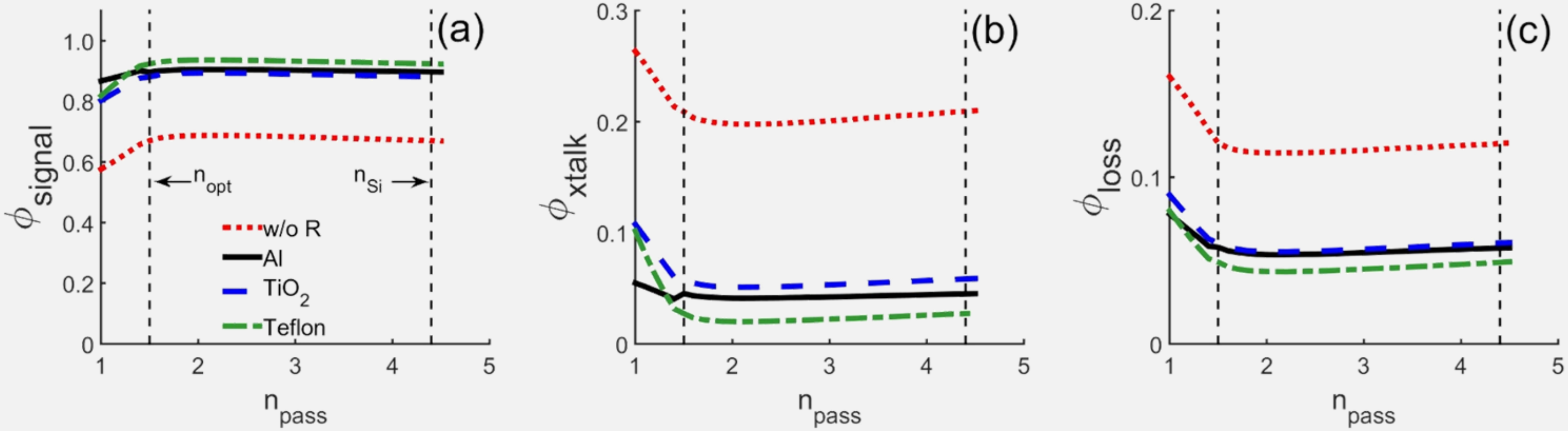


- FOM

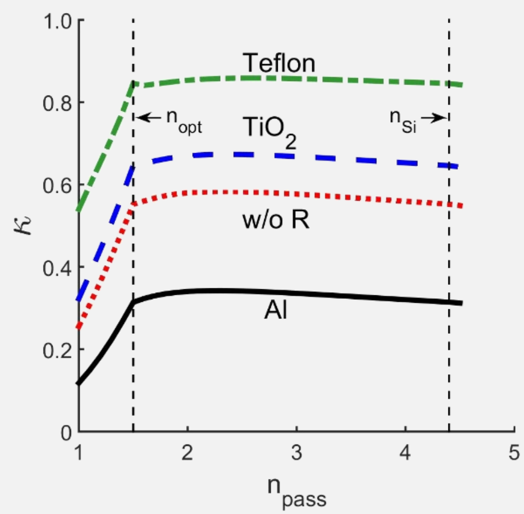


Results for the varying properties of passivation layer

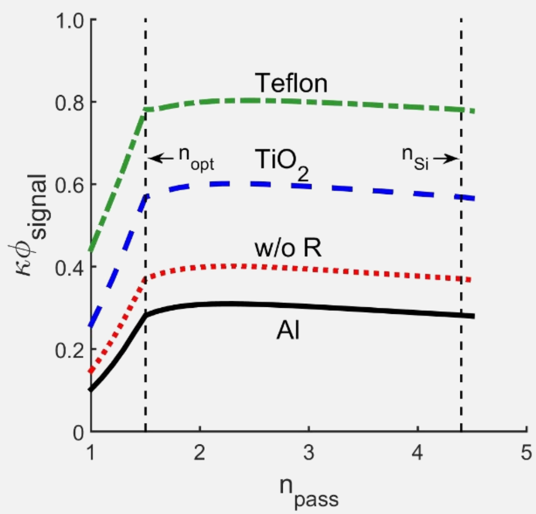
- Quantum distribution



- LCE



- FOM



Results for the varying properties of reflector

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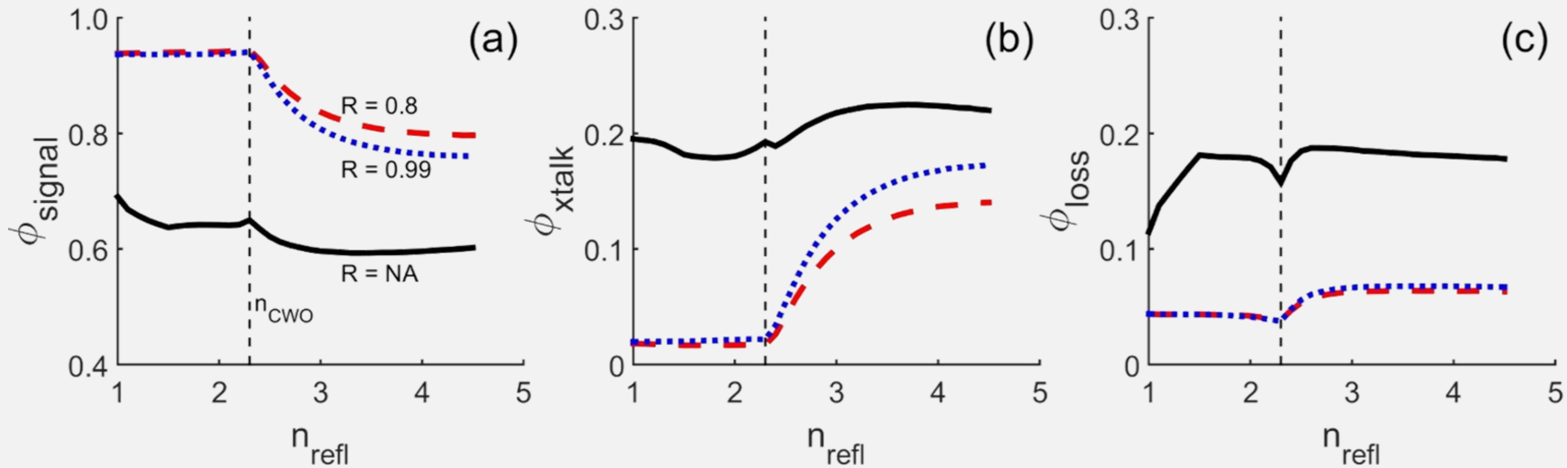
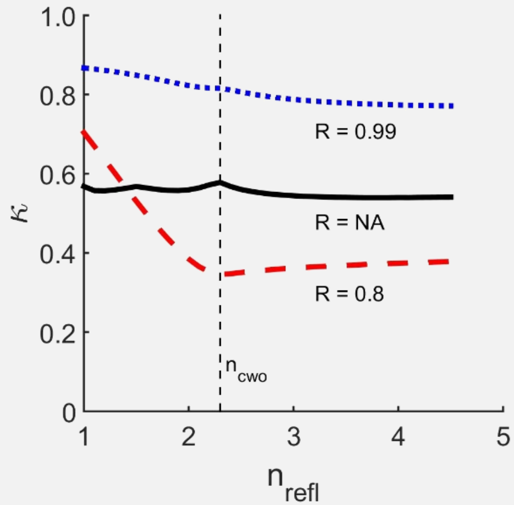
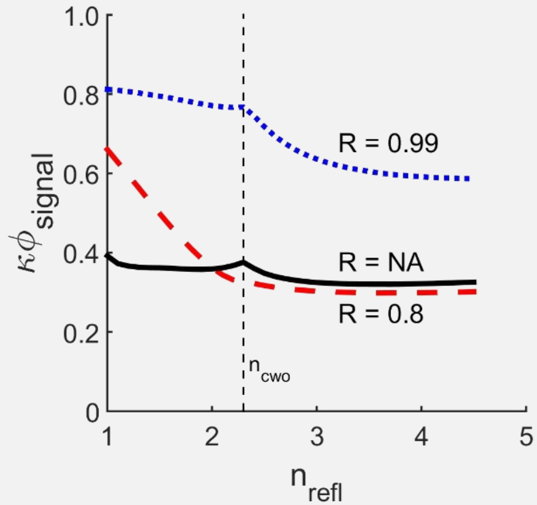
- Quantum distribution



- LCE



- FOM



Conclusion

- Optimal dimension of each layer of linear detector arrays is described in the table

Parameter	Definition	Optimal value
t_{opt}	Thickness of the optical glue	< 100 μm
n_{opt}	Refractive index of optical glue	$n_{opt} \approx n_{scn}$
t_{pass}	Thickness of passivation layer	-
n_{pass}	Refractive index of passivation layer	$n_{opt} \leq n_{pass} \leq n_{pd}$
R	Reflection coefficient of reflector	≥ 0.95 (for LCE ≥ 0.7)

- To analyze the performance of detector systems, remainder cascade stage need to be considered.
- Calculate the detective quantum efficiency, and compare with the other candidates of scintillator
- Need to be validate with the experiment

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Thanks for your

kind attention