Politecnico di Torino
Department of Electronics and Telecommunications

PhotoNext Researcher's Day

Modeling of Ge-on-Si photodetector for wide-band Silicon Photonics applications

June 19, 2023

Matteo G. C. Alasio

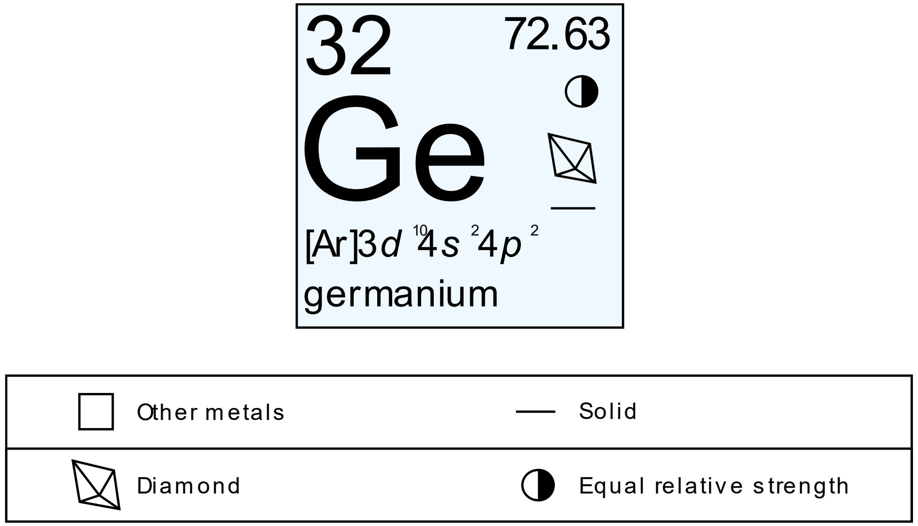
Ge-on-Si *pin* photodetectors

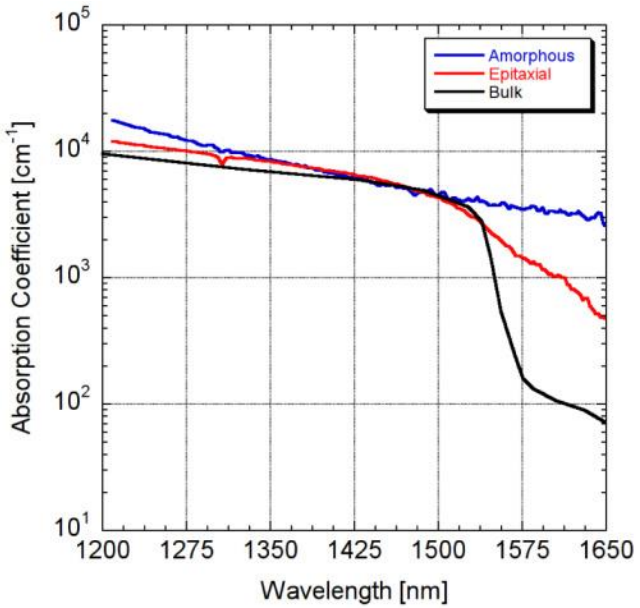
Materials:
- Si
- Ge
- SiO
- SiN
- metals

Light coupling:
- vertical device
- waveguide devices
  - evanescent coupling
  - butt coupling

Device structures:
- *pin* diode
  - Vertical
  - Lateral

Figures of merit:
- Dark current
- Responsivity
- Bandwidth
- Gain





https://doi.org/10.1364/OME.1.000856

Ge-on-Si *pin* photodetectors

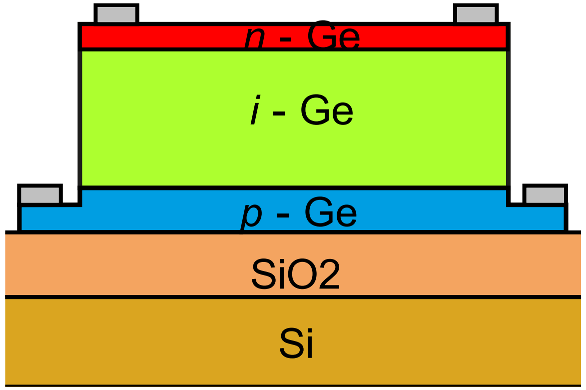
Materials:
- Si
- Ge
- SiO
- SiN
- metals

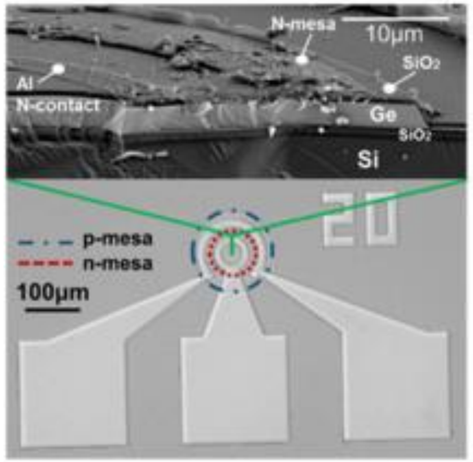
Light coupling:
- vertical device
- waveguide devices
  - evanescent coupling
  - butt coupling

Device structures:
- *pin* diode
  - Vertical
  - Lateral

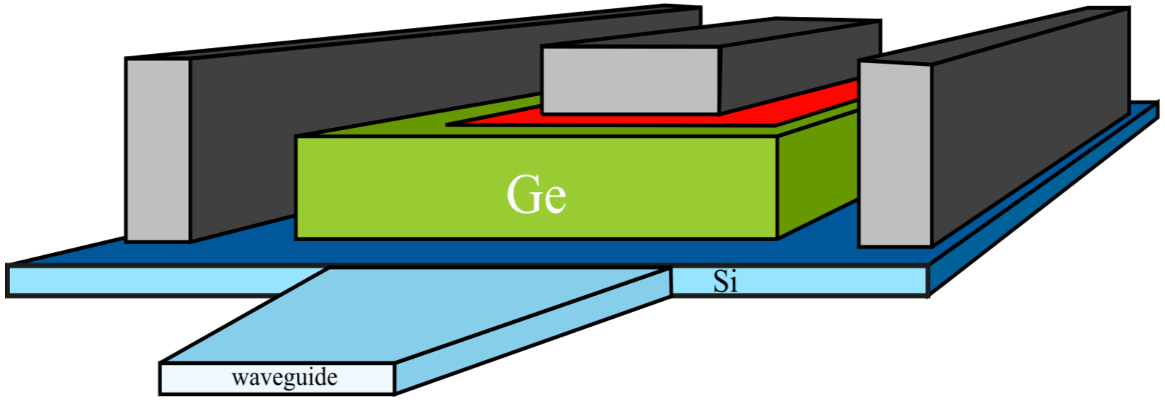
Figures of merit:
- Dark current
- Responsivity
- Bandwidth
- Gain

vertical detector





waveguide detector



https://doi.org/10.1364/PRJ.5.000702

Ge-on-Si *pin* photodetectors

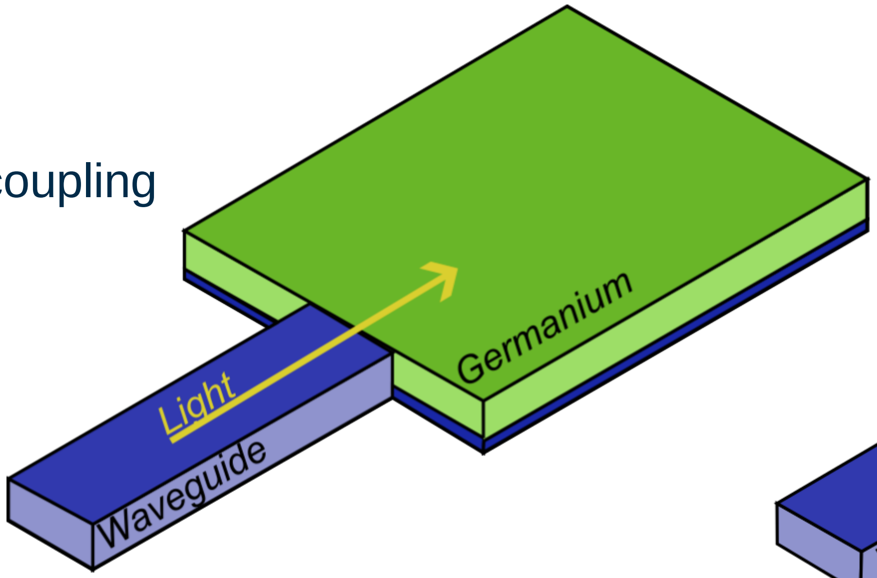
Materials:
- Si
- Ge
- SiO
- SiN
- metals

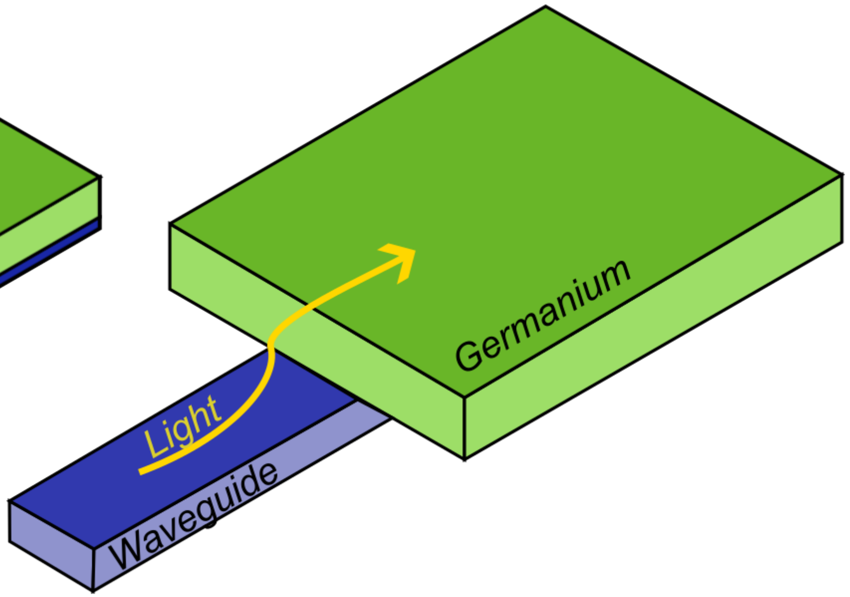
Light coupling:
- vertical device
- waveguide devices
  - evanescent coupling
  - butt coupling

Device structures:
- *pin* diode
  - Vertical
  - Lateral

Figures of merit:
- Dark current
- Responsivity
- Bandwidth
- Gain

butt coupling





evanescent coupling

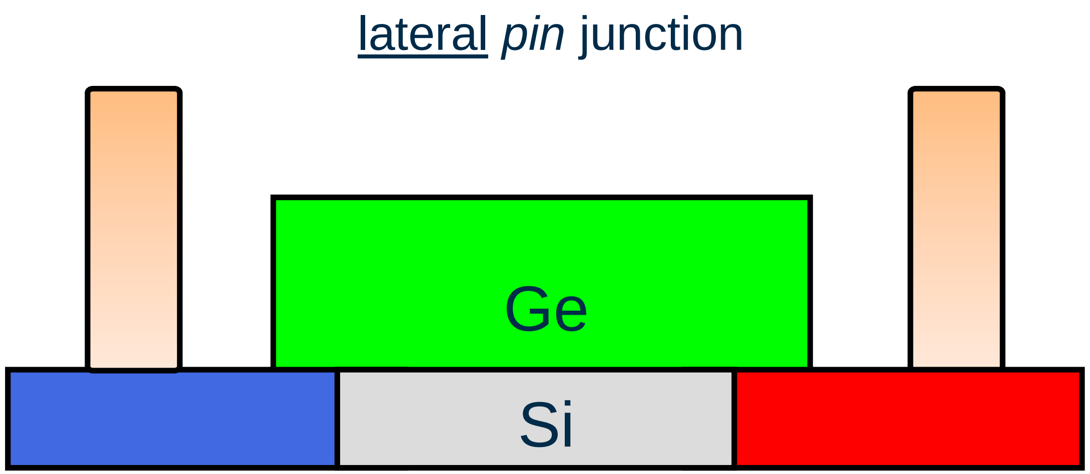
Ge-on-Si *pin* photodetectors

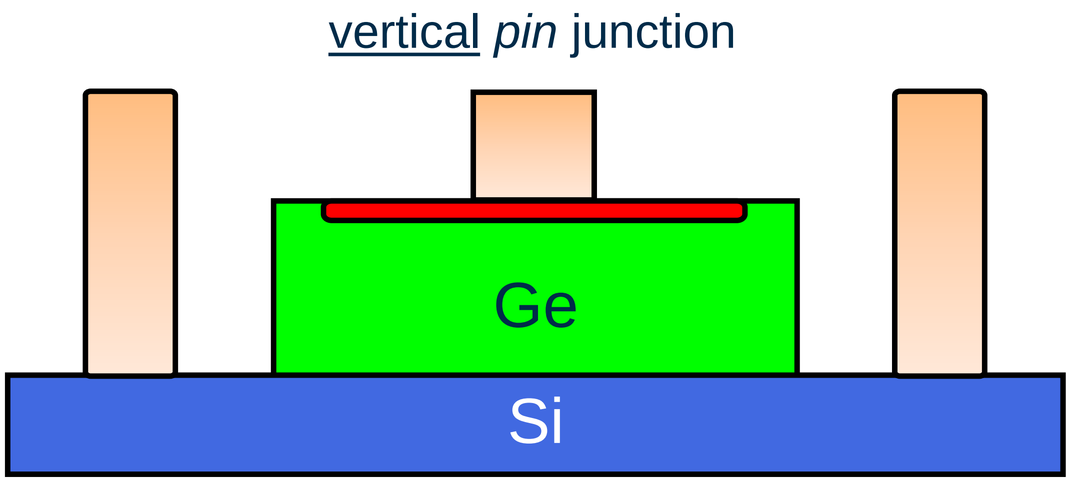
Materials:
Si
Ge
SiO
SiN
metals

Light coupling:
vertical device
waveguide devices
- evanescent coupling
- butt coupling

Device structures:
pin diode
- Vertical
- Lateral

Figures of merit:
Dark current
Responsivity
Bandwidth
Gain





Ge-on-Si *pin* photodetectors

Materials:
- Si
- Ge
- SiO
- SiN
- metals

Light coupling:
- vertical device
- waveguide devices
  - evanescent coupling
  - butt coupling

Device structures:
- *pin* diode
  - Vertical
  - Lateral

Figures of merit:
- Dark current
- Responsivity
- Bandwidth

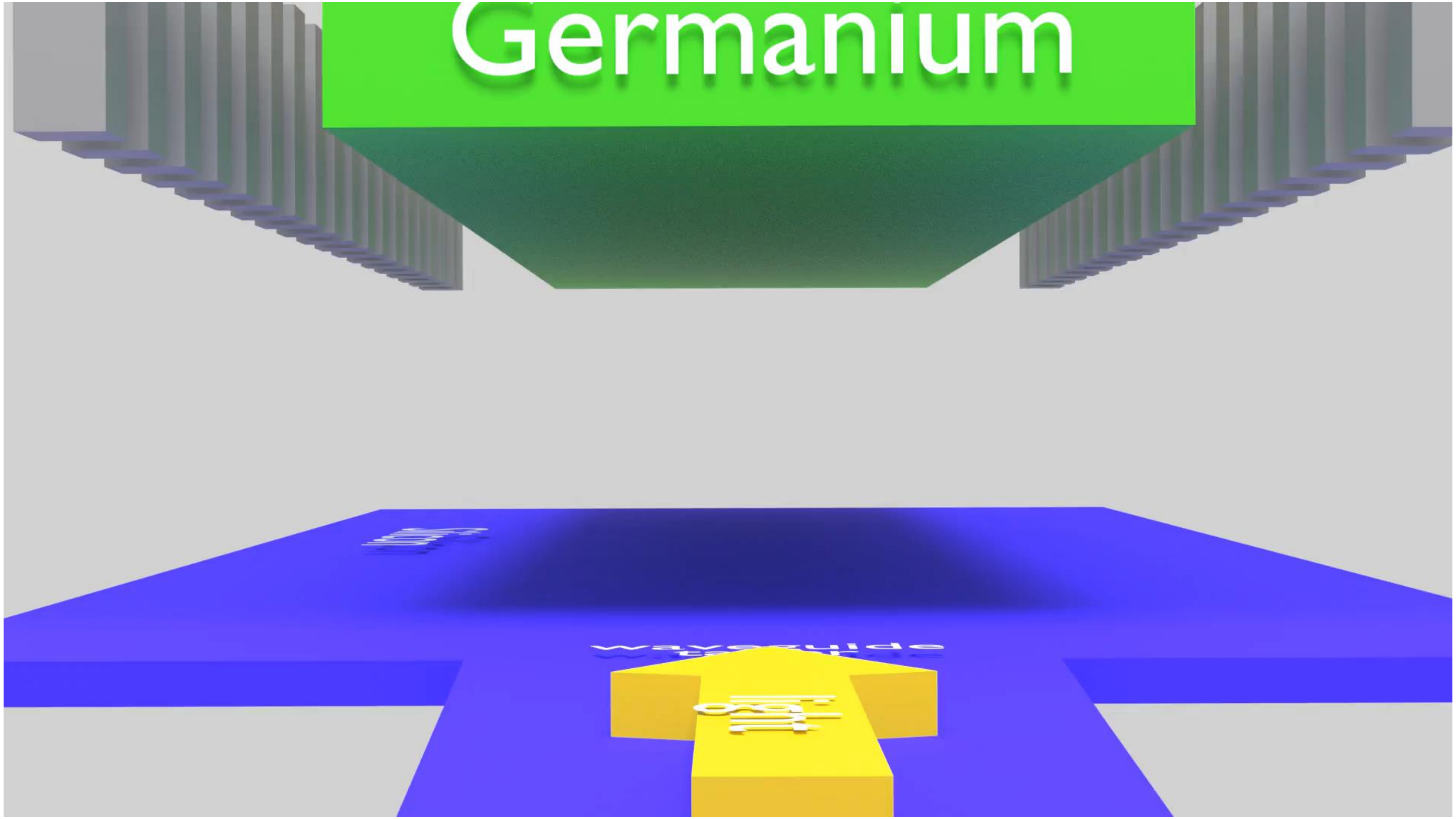
Responsivity: ratio between photocurrent and input optical power

$$R = \frac{I_L}{P_{op}}$$

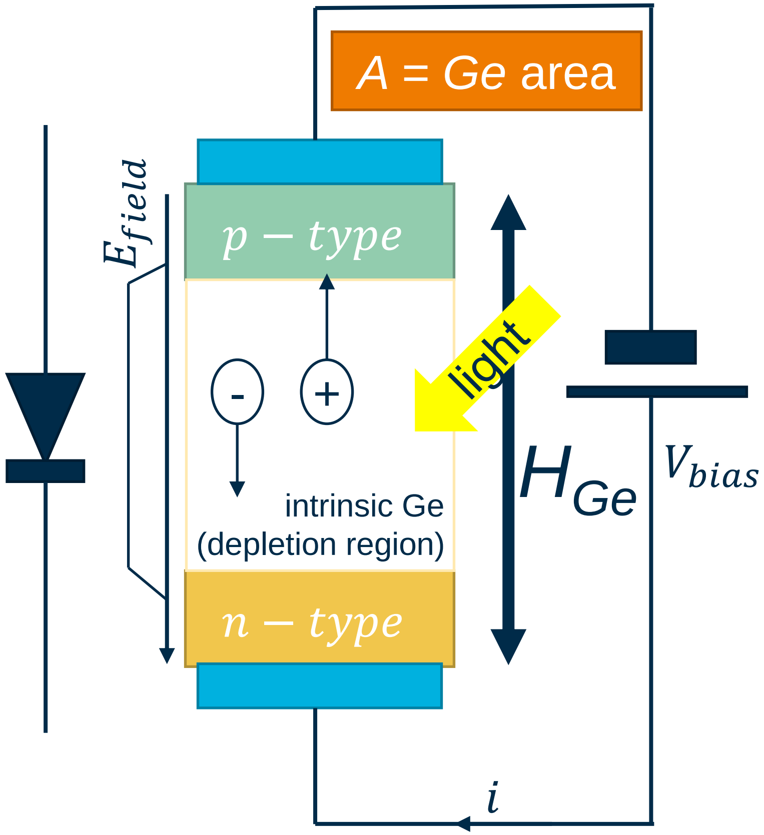
Modulation bandwidth

$$\hat{I}_L(f_m) = R(f_m)\hat{P}_{op}(f_m)$$

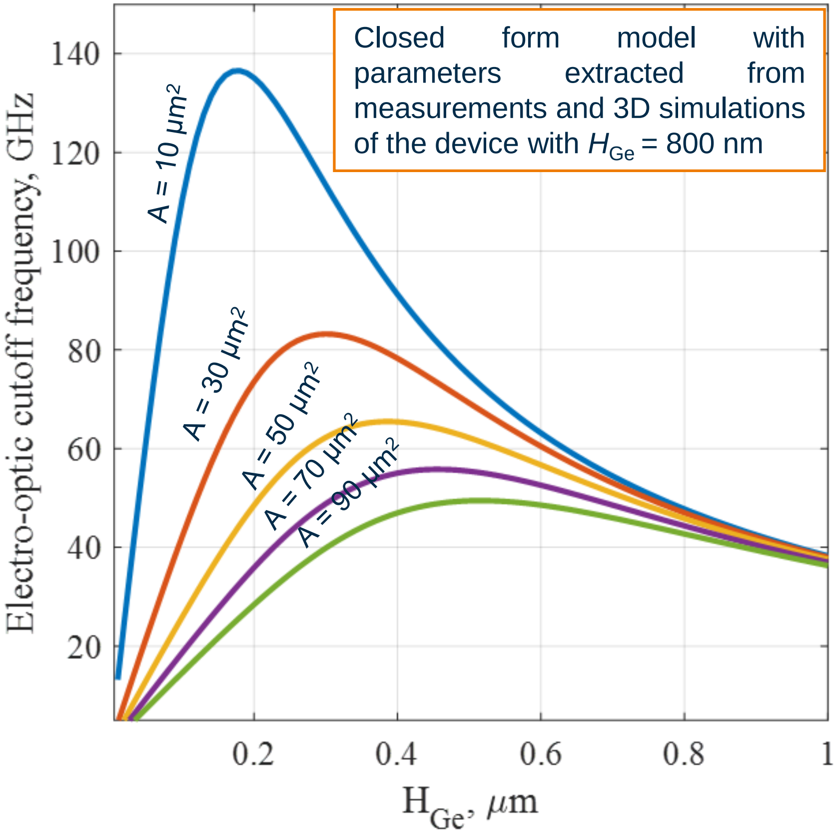
limited by
- **device capacitance**
- **transit time** of photogenerated carriers


Germanium

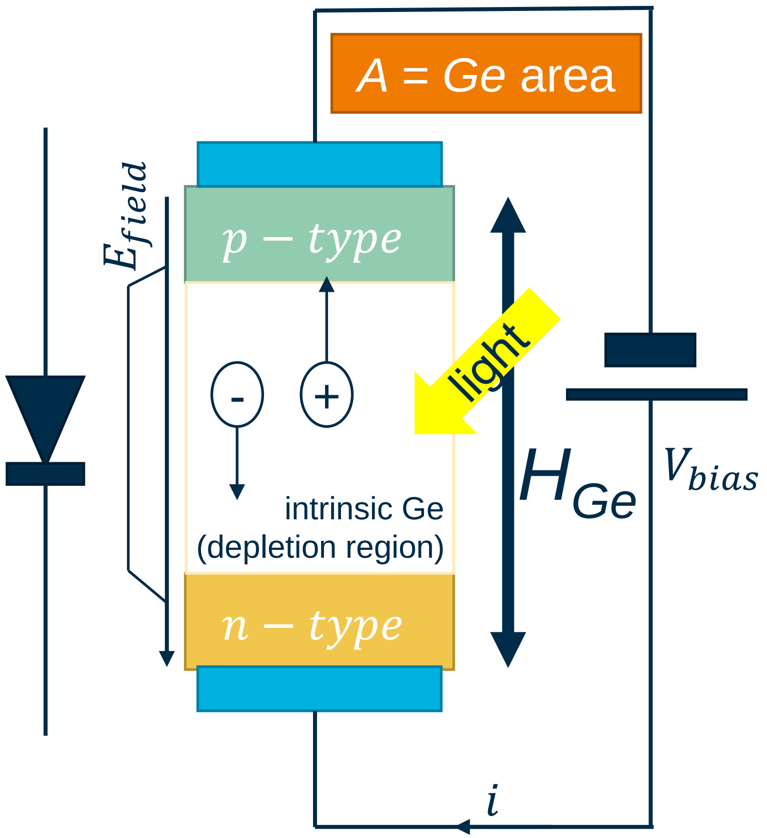
Efficiency-speed tradeoff



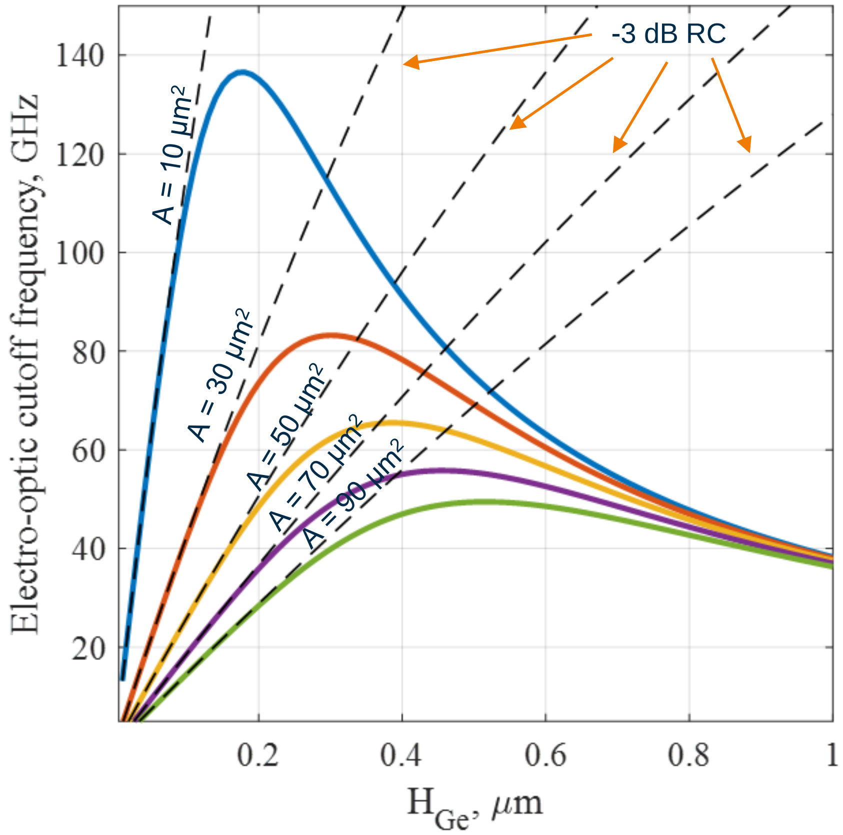
$$f_{-3\ dB,\,RC} \propto H_{\mathrm{Ge}}, \quad f_{-3\ dB,tr} \propto \frac{1}{H_{\mathrm{Ge}}}$$



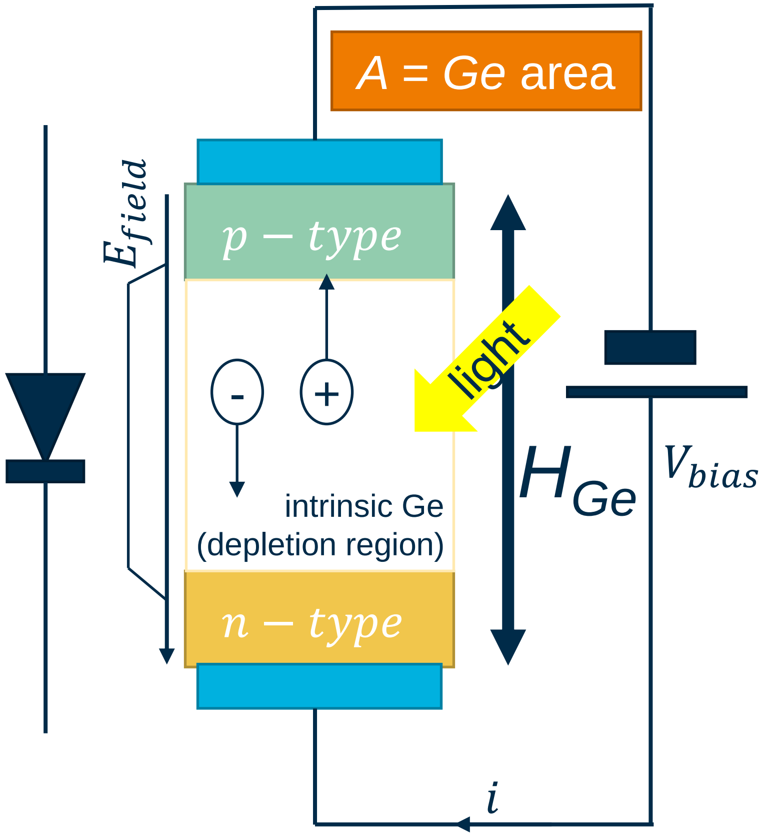
Efficiency-speed tradeoff



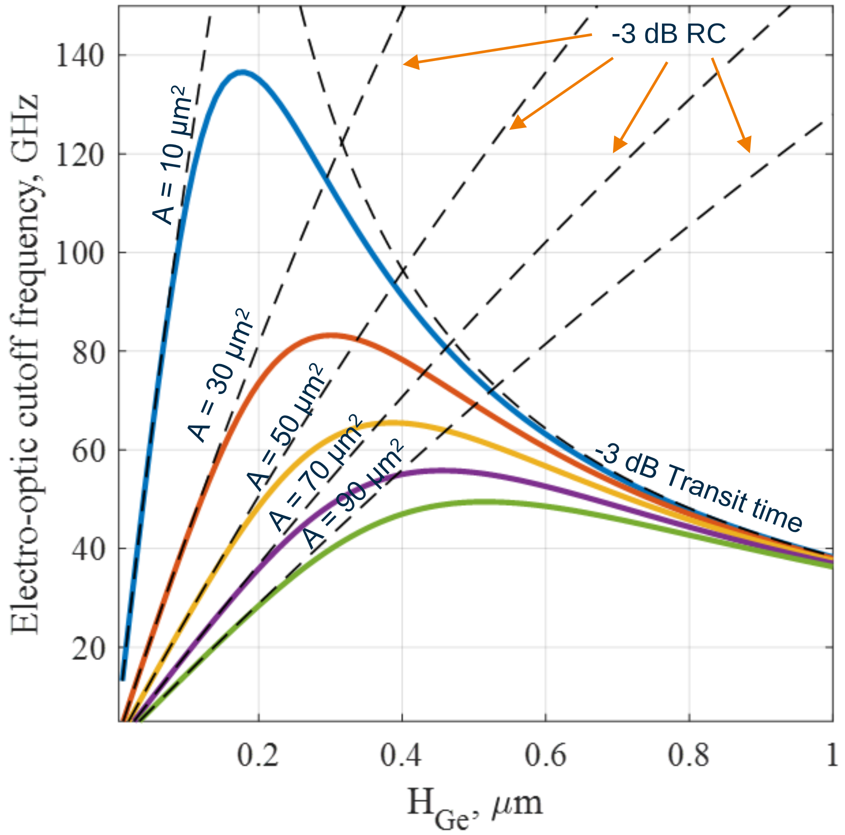
$$f_{-3\ dB,\ RC} \propto H_{Ge}, \quad f_{-3\ dB,tr} \propto \frac{1}{H_{Ge}}$$



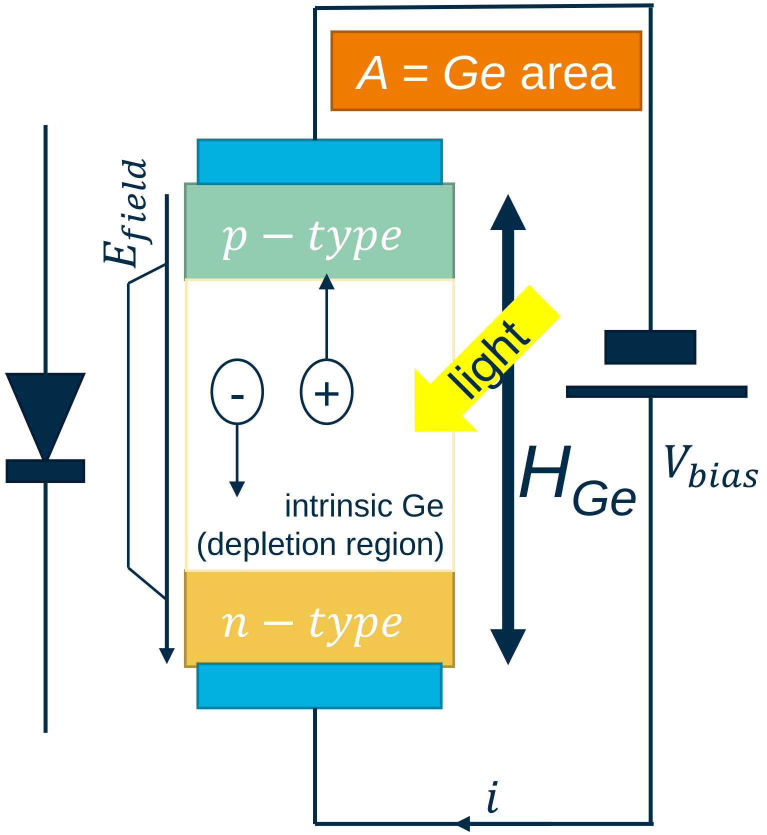
Efficiency-speed tradeoff



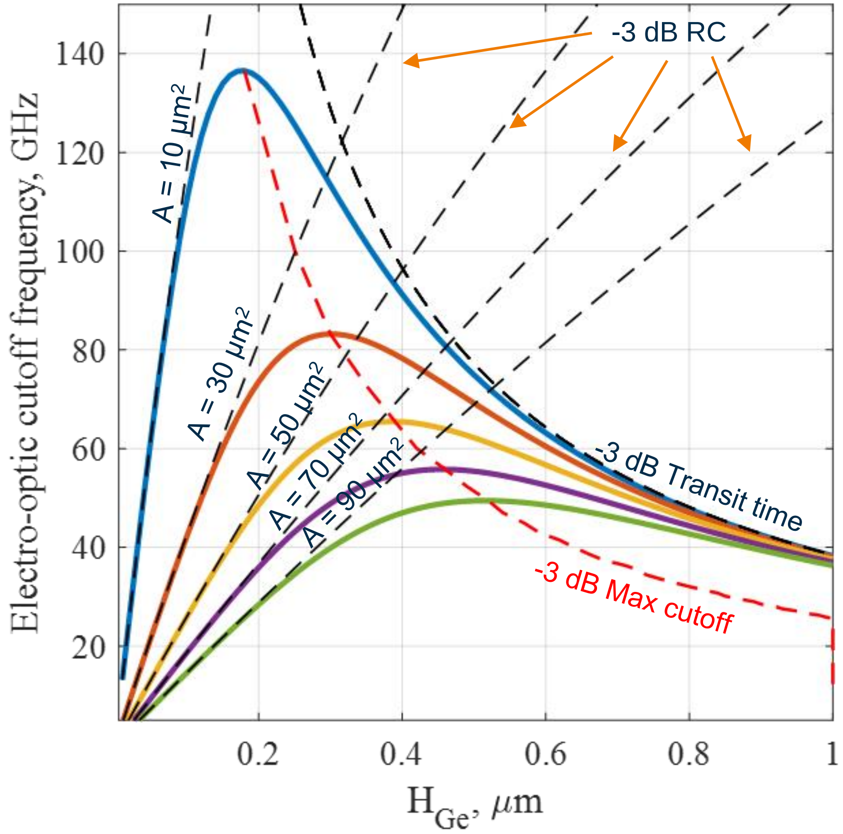
$$f_{-3\ dB,\ RC} \propto H_{Ge}, \quad f_{-3\ dB,tr} \propto \frac{1}{H_{Ge}}$$



Efficiency-speed tradeoff



$$f_{-3\ dB,\,RC} \propto H_{Ge},\quad f_{-3\ dB,tr} \propto \frac{1}{H_{Ge}}$$



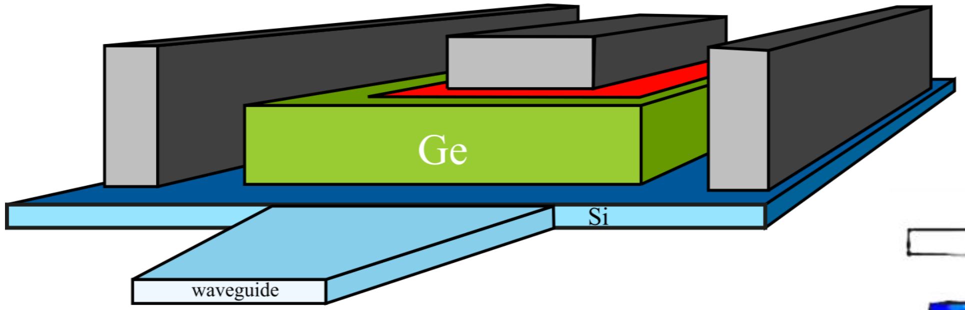
3D multiphysics modeling

Optical problem:
Maxwell's equations

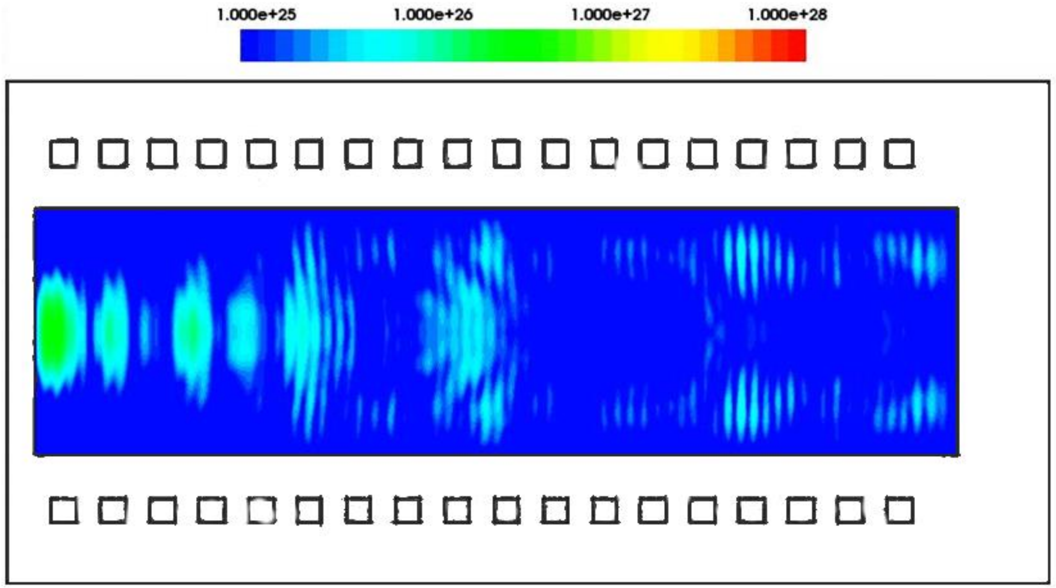
$$\frac{\partial D}{\partial t} = \nabla \times H - J \qquad \nabla \cdot D = 0$$

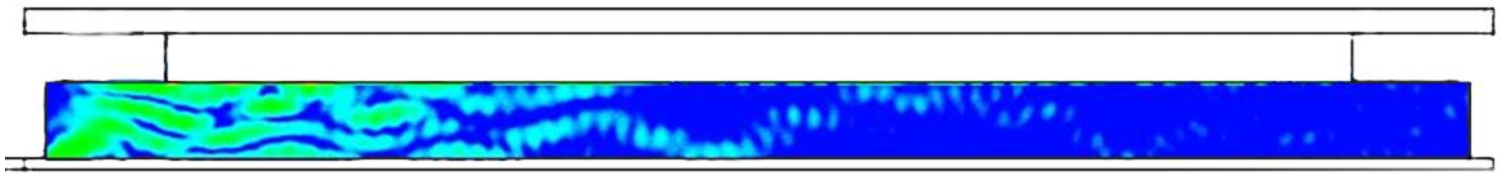
$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad D = \varepsilon_r \varepsilon_0 E$$

$$\nabla \cdot B = 0 \qquad H = \frac{1}{\mu_r \mu_0} B$$



Optical generation rate (cm^{-3} s^{-1})





3D multiphysics modeling

Optical problem: Maxwell's equations

$$\frac{\partial D}{\partial t} = \nabla \times H - J \qquad \nabla \cdot D = 0$$

$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad D = \varepsilon_r \varepsilon_0 E$$

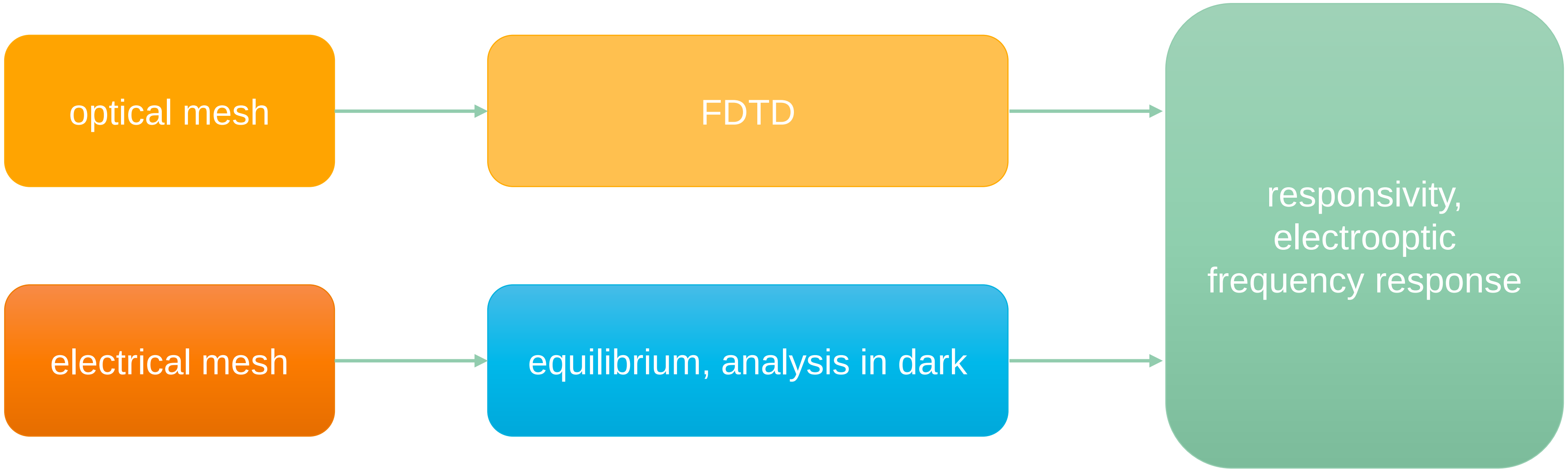
$$\nabla \cdot B = 0 \qquad H = \frac{1}{\mu_r \mu_0} B$$

Electrical problem: drift-diffusion model

$$\nabla^2 \phi = -\frac{q}{\varepsilon}\rho \qquad \rho = (+q\,N_D^+) + (-q\,N_A^-) + (+qp) + (-qn)$$

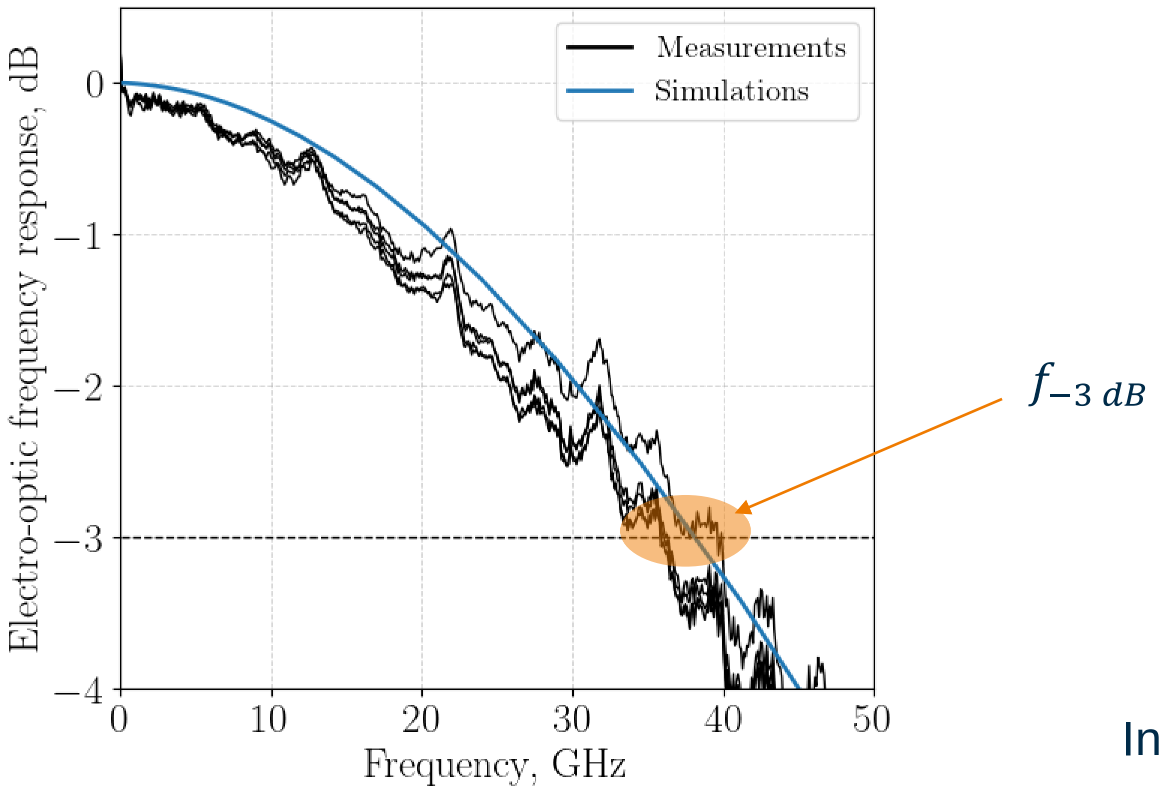
$$\frac{\partial p}{\partial t} + \frac{1}{q}\nabla \cdot J_p + U_p = 0 \qquad J_n = J_{n,t} + J_{n,d} = -qn\mu_n \nabla\phi + qD_n \nabla n$$

$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla \cdot J_n + U_n = 0 \qquad J_p = J_{p,t} + J_{p,d} = -qp\mu_p \nabla\phi - qD_p \nabla p$$



Model validation

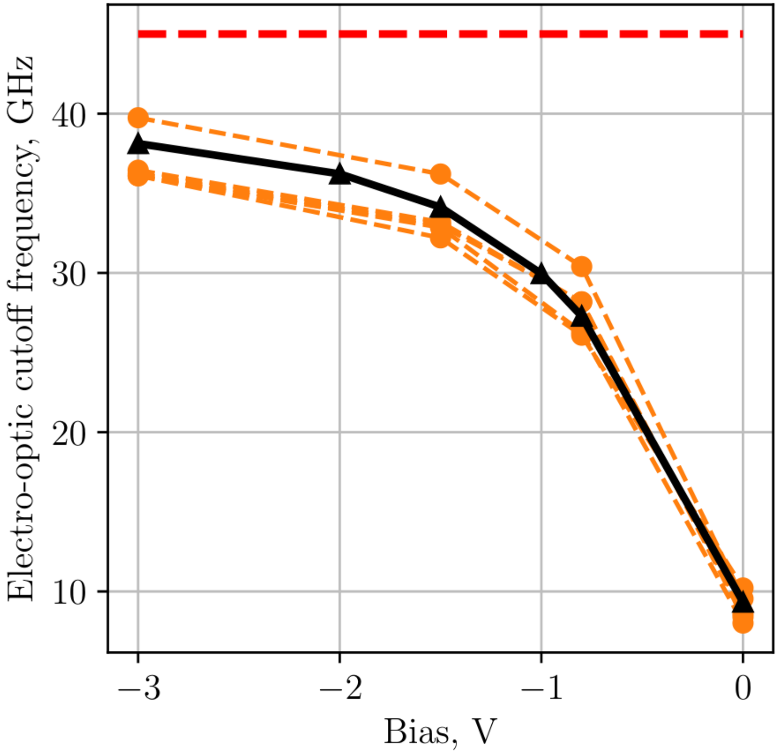
From the electro-optic frequency response, we extract the -3 dB electro-optic cutoff frequency, and we use it for comparisons with measurements and parameter calibration.



Bias = -3 V
Input optical power = 100 µW

Model validation: E/O cutoff frequency vs bias

The model has been validated against 6 WPDs, considering **yield** and **bias sensitivities**. In all cases the simulations achieve a good agreement with measurements.



Simulation
Measurements
Closed-form model

Input optical power = 100 µW