

Mixed device/circuit model of the high-speed p-i-n photodiode

A. Chizh, S. Malyshev, and Y. Vasileuski
chizh@ieee.org, malyshev@ieee.org

Laboratory of Semiconductor Optoelectronics

Institute of Electronics

National Academy of Sciences of Belarus

Outline

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 - Motivation for mixed device/circuit model
 - Motivation for 2-D physical simulation
- **Model formulation**
- **Model features**
- **Simulation examples**
 - p-i-n photovaractor
 - optoelectronic mixer based on p-i-n photodiode

Introduction

- **High-speed photodetectors based on All-BV compounds are used in the wide range of microwave photonics applications for**
 - optical signal detection
 - photonic generation of microwaves
 - frequency conversion of optically-transmitted microwave signals
 - optical control of microwave circuits
- **Vertically-illuminated InGaAs/InP p-i-n photodiodes are the most commonly used photodetectors due to**
 - operation at the wavelength range of 800÷1650 nm
 - planar and reliable fabrication technology
 - relatively low price

Introduction & Motivation

- From microwave circuit point of view the high-speed p-i-n photodiode can be used as
 - microwave generator
 - varactor
 - switch
 - mixer



- For proper p-i-n photodiode design and matching with microwave circuit it is necessary to simulate photodiode S-parameters



- This requires the mixed device/circuit simulation both in time and frequency domains

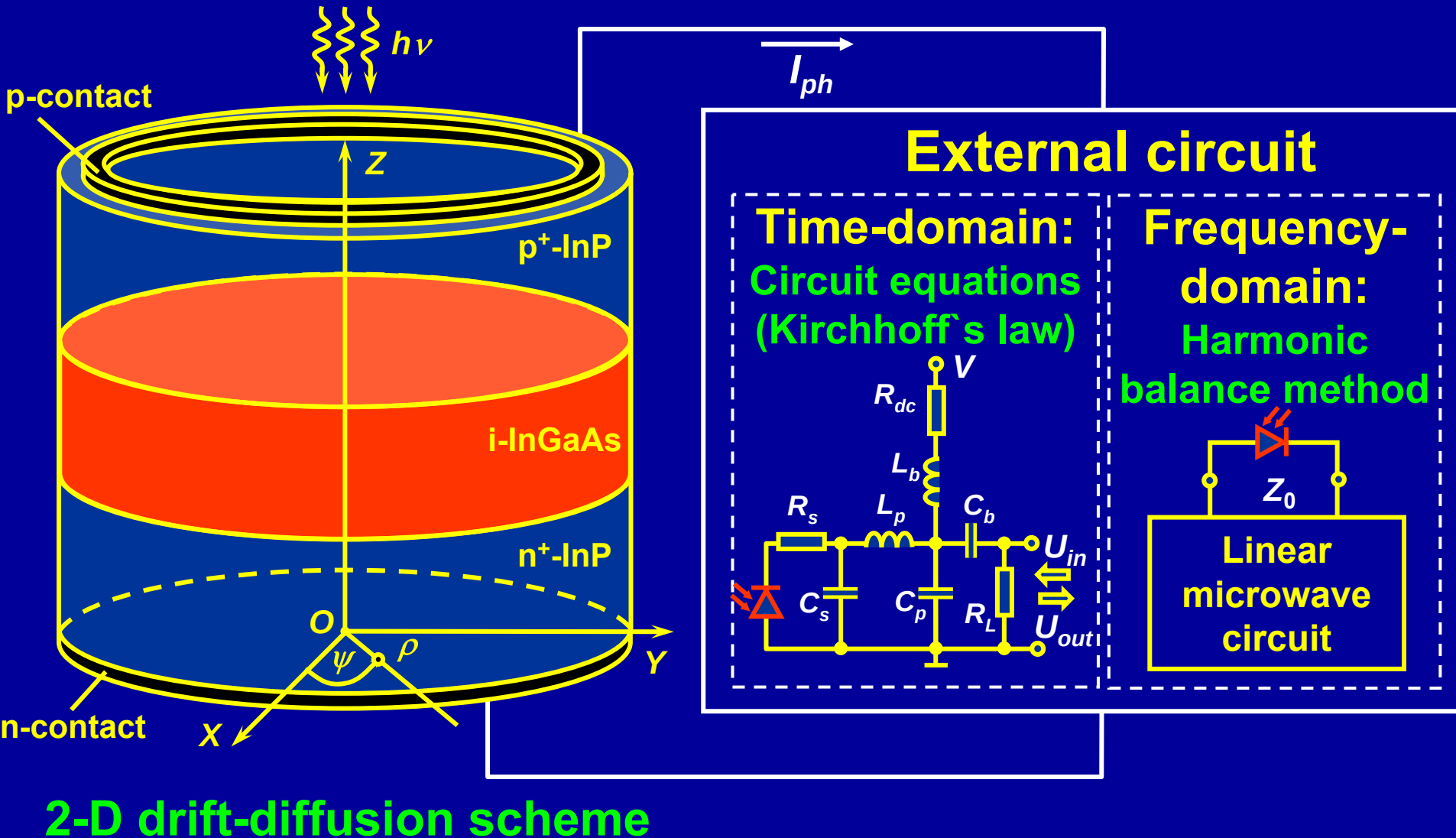
Introduction & Motivation

- Most of the existing p-i-n photodiode models are based on 1-D drift-diffusion scheme and suitable for time-domain simulation
- 1-D models can not take into account
 - contact geometry (large area / high-power photodiodes)
 - nonuniform optical illumination (large area photodiodes)
 - surface recombination (large area photodiodes)
 - edge capacitance (small area photodiodes)



- The main goal of this paper is development of mixed device/circuit model based on 2-D drift-diffusion scheme

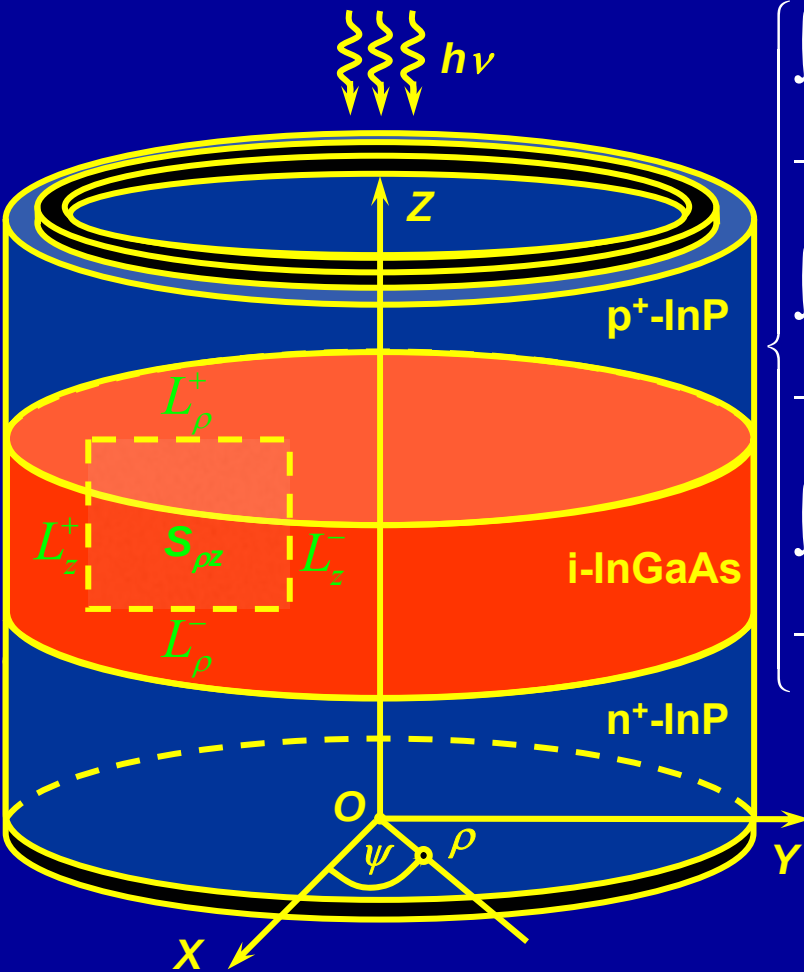
Model: basic principle



2-D drift-diffusion scheme

Model: 2-D drift-diffusion scheme

Axial symmetry: 3D $\rightarrow$ 2D, cylindrical coordinates



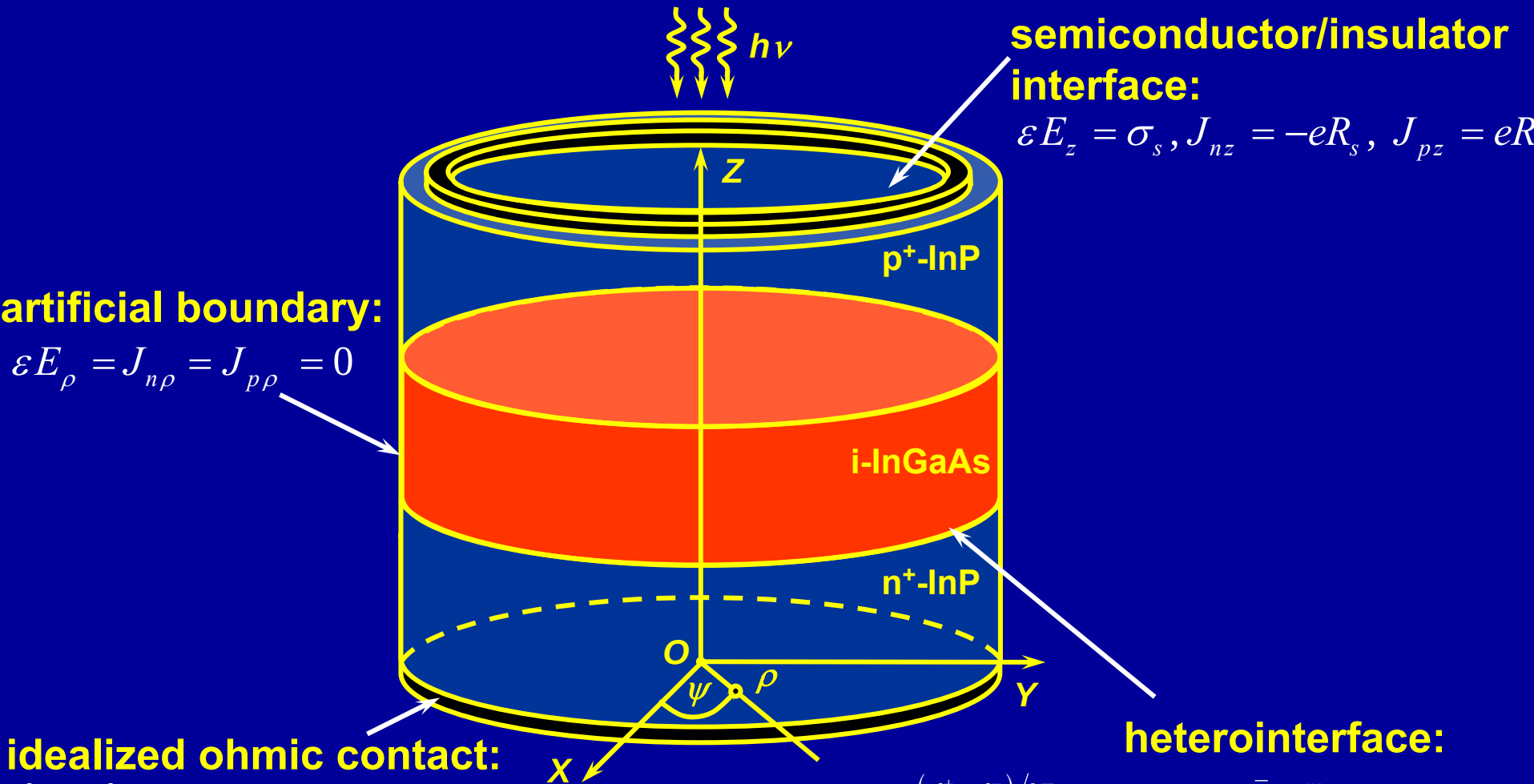
$$\left\{ \begin{aligned} & \int_{L_\rho^+} \varepsilon E_z \rho d\rho - \int_{L_\rho^-} \varepsilon E_z \rho d\rho + \int_{L_z^+} \varepsilon E_\rho \rho dz - \\ & - \int_{L_z^-} \varepsilon E_\rho \rho dz = e \int_{S_{\rho z}} [n - p + N] \rho d\rho dz \\ & \int_{L_\rho^+} J_{nz} \rho d\rho - \int_{L_\rho^-} J_{nz} \rho d\rho + \int_{L_z^+} J_{n\rho} \rho dz - \\ & - \int_{L_z^-} J_{n\rho} \rho dz = e \int_{S_{\rho z}} [R - \alpha P_{opt} I_0 / h\nu - \partial n / \partial t] \rho d\rho dz \\ & \int_{L_\rho^+} J_{pz} \rho d\rho - \int_{L_\rho^-} J_{pz} \rho d\rho + \int_{L_z^+} J_{p\rho} \rho dz - \\ & - \int_{L_z^-} J_{p\rho} \rho dz = e \int_{S_{\rho z}} [\alpha P_{opt} I_0 / h\nu - R + \partial p / \partial t] \rho d\rho dz \end{aligned} \right.$$

$$J_{nz} = \mu_n n \frac{\partial f_n}{\partial z}, J_{n\rho} = \mu_n n \frac{\partial f_n}{\partial \rho}$$

$$J_{pz} = \mu_p p \frac{\partial f_p}{\partial z}, J_{p\rho} = \mu_p p \frac{\partial f_p}{\partial \rho}$$

The box integration approach of the finite difference method is applied for discretization

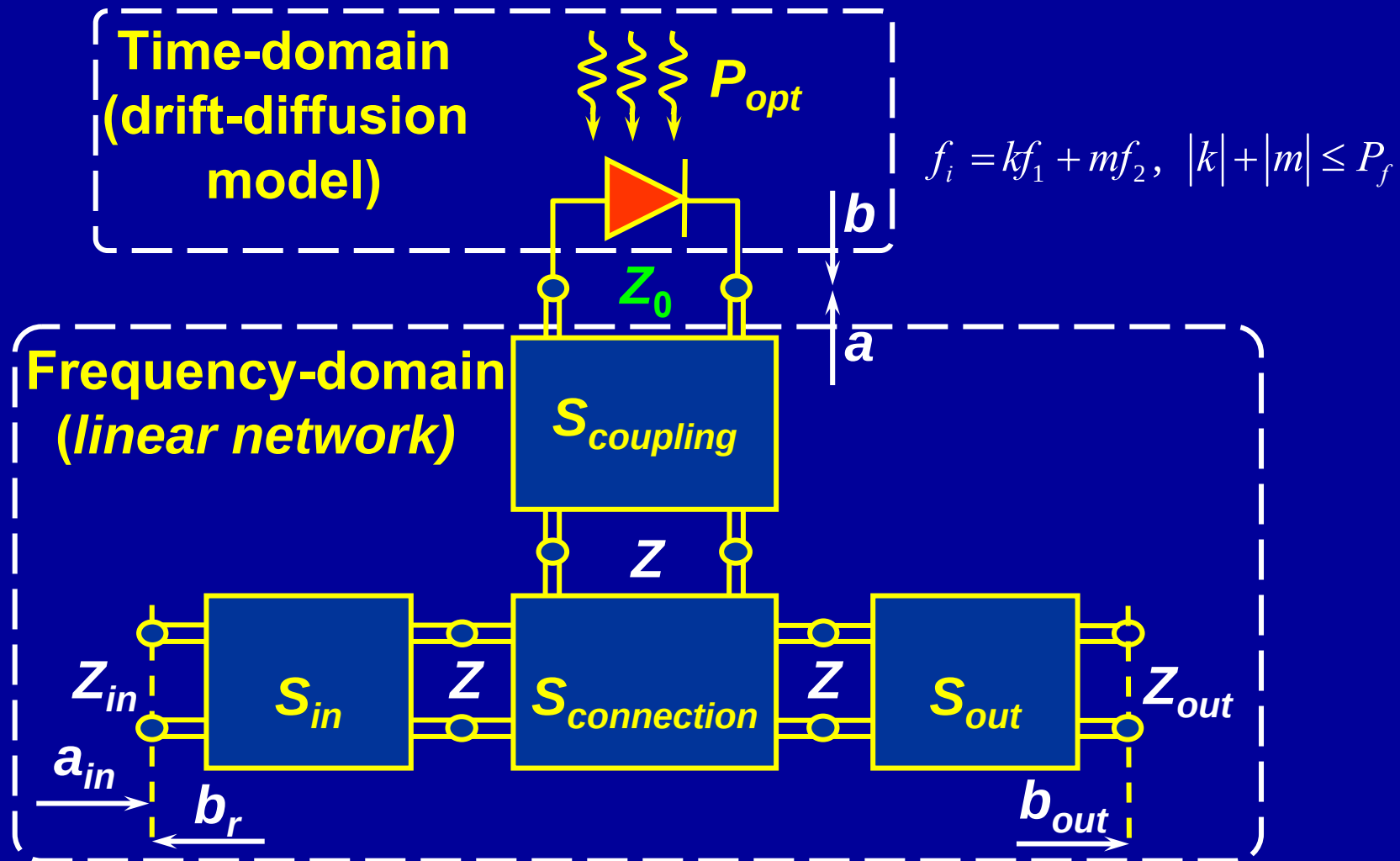
Model: boundary conditions



$$J_{nz} = \frac{em_n^{\max}}{2\pi^2 \hbar^3} \int_{E_c^{\min}}^{+\infty} \frac{(e^{(f_n^+ - f_n^-)/kT} - 1) d\bar{E}}{1 + e^{\frac{f_n^+ - f_n^-}{kT}} + e^{\frac{\bar{E} - f_n^-}{kT}} + e^{\frac{f_n^+ - \bar{E}}{kT}}} \int_{\bar{E} - \gamma_n}^{\bar{E} - E_c^{\max}} T_e(E_\perp) dE_\perp$$

$$\gamma_n = E_c^{\max} - (\bar{E} - E_c^{\min}) m_n^{\max} / m_n^{\min}$$

Model: harmonic balance



$U(t) \rightarrow$ 2-D drift-diffusion transient calculation $\rightarrow I_{ph}(t)$

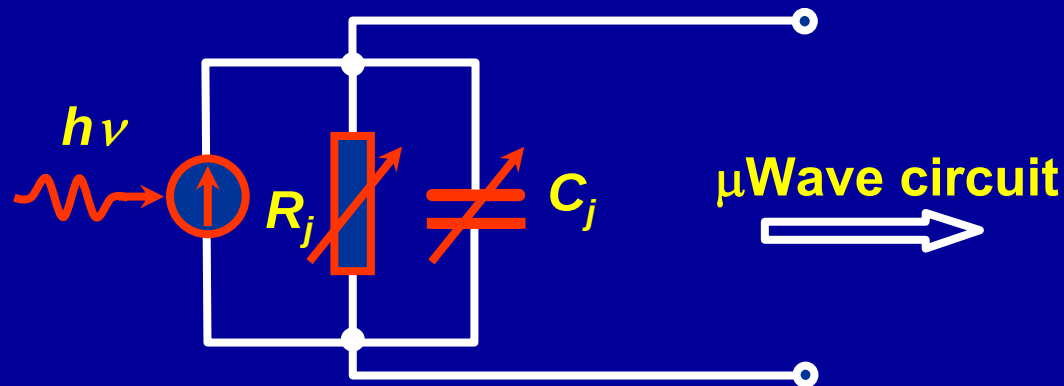
$$U_i^{(k)} = \left(U_i^{(k-1)} - I_i^{(k-1)} Z_0 \right) (1 + \Gamma_{li}) / 2 + T_i U_i^{in} \sqrt{Z_0 / Z_i^{in}}, \quad i = \overline{1, N_f}$$

Model features

- **Drift-diffusion scheme**
 - Axial symmetry: 3D $\rightarrow$ 2D, cylindrical coordinates
 - Poisson's, the electron and hole current continuity equations
 - Basis: (φ, f_n, f_p)
 - Fermi-Dirak distribution function for electrons and holes
 - Mobility dependent on electric field and doping density
 - Thermionic emission and tunneling through the heterointerface
- **Harmonic balance method**
 - Linear circuit is represented by S-matrix
 - 2-tone HB simulation
 - Model algorithm: fixed-point iterative scheme
- **Model realization**
 - Interpolation method for input All-BV material data
 - Box integration approach of the finite difference method
 - Damped Newton method (coupled approach)

Simulation example: p-i-n photovaractor

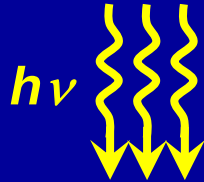
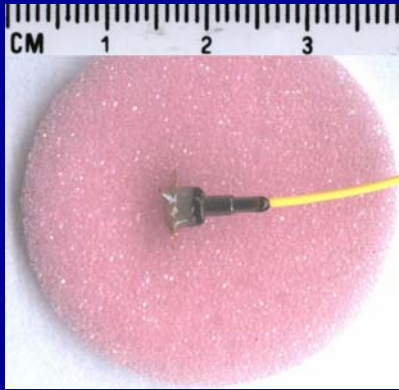
- **Application**
 - microwave phase shifting and attenuation
 - frequency tuning of filter or oscillator
 - optically-controlled nonlinear microwave transmission lines
 - remote optical control by means of fiber-optic links
- **Photovaractor based on the effect of p-n junction capacitance change under illumination**



In this application the main requirements to the photodiode

- high capacitance ratio
- low control optical power
- high junction resistance (high quality factor)

35 μm -diameter InGaAs/InP p-i-n photovaractor



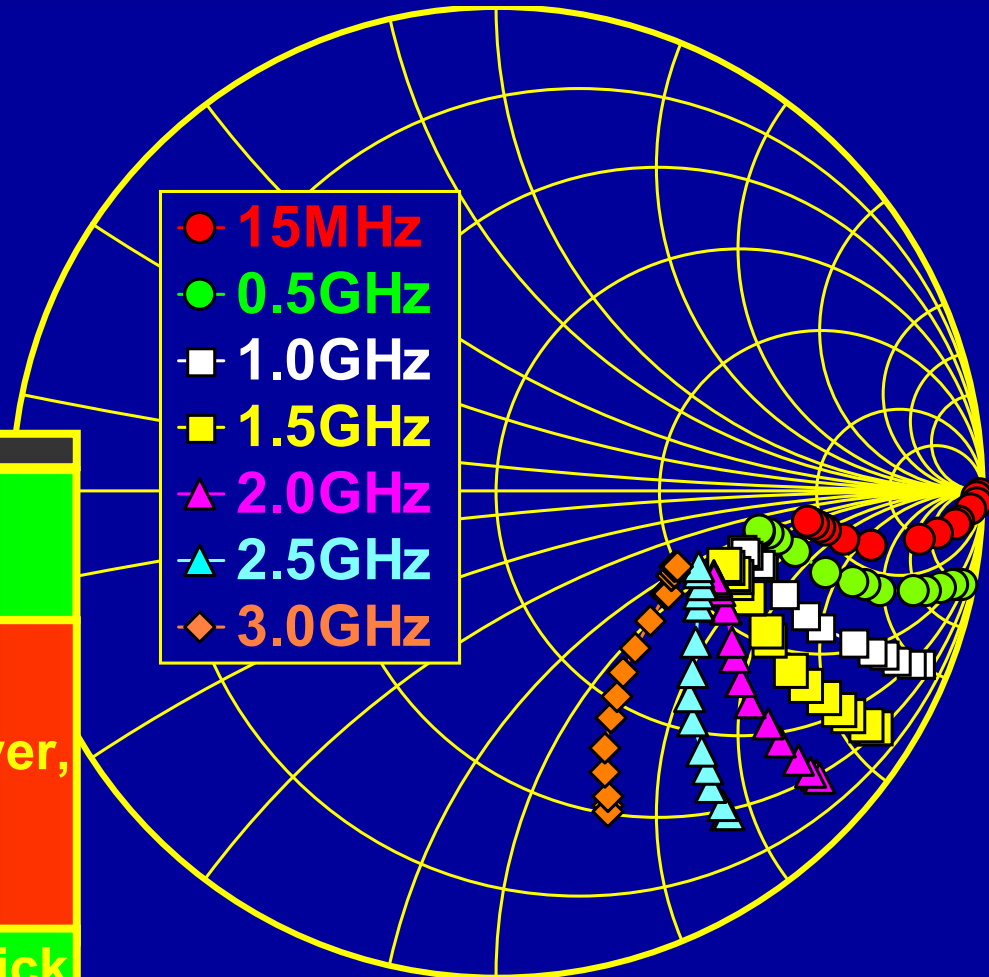
n^0 -InGaAsP
top layer,
1 μm -thick

p^+ -region,
 $2 \cdot 10^{18} \text{cm}^{-3}$

n^0 -InGaAs absorption layer,
3 μm -thick, 10^{15}cm^{-3}

n^+ -InGaAsP contact layer, 1 μm -thick

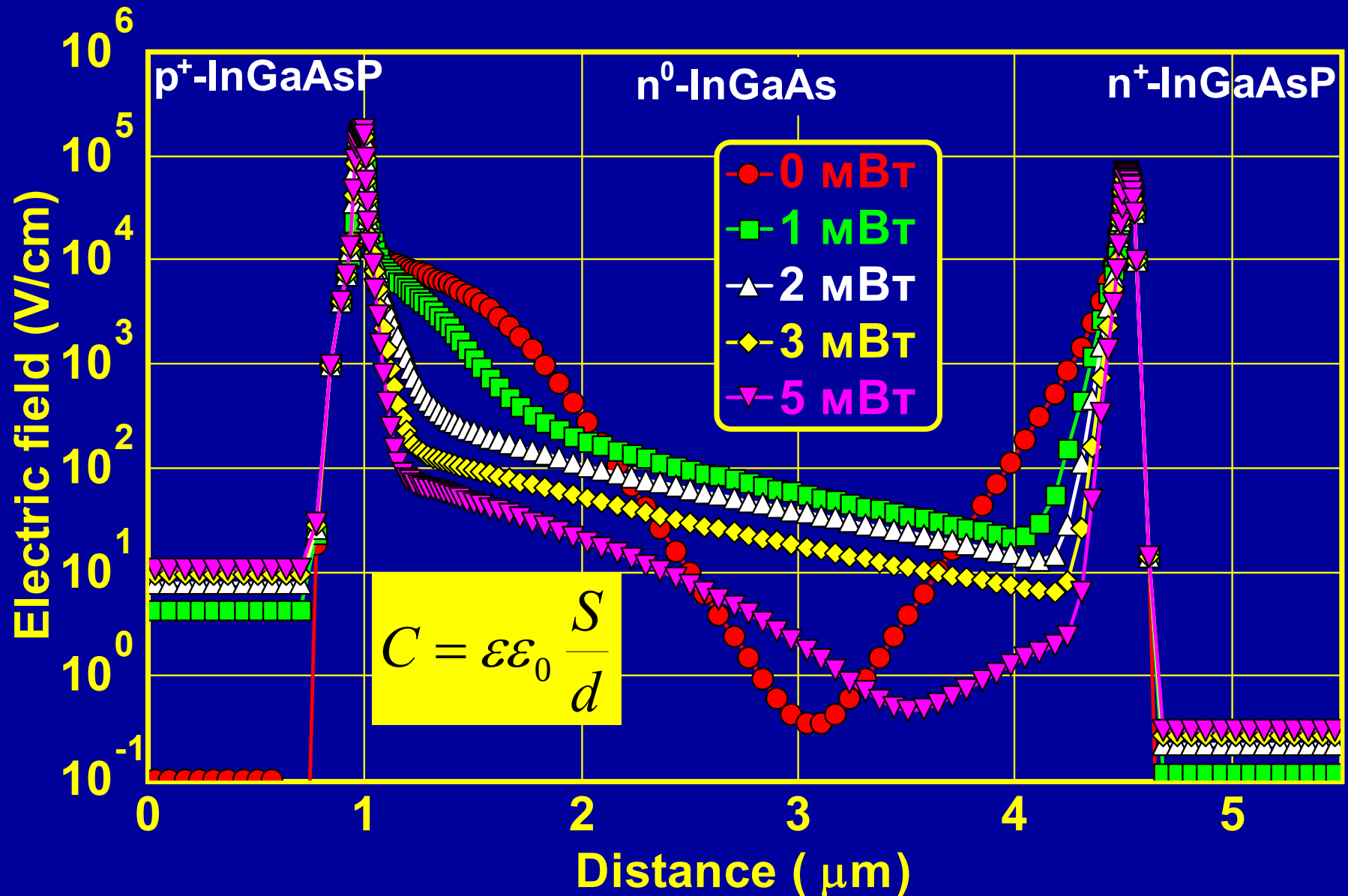
semi-insulated InP substrate



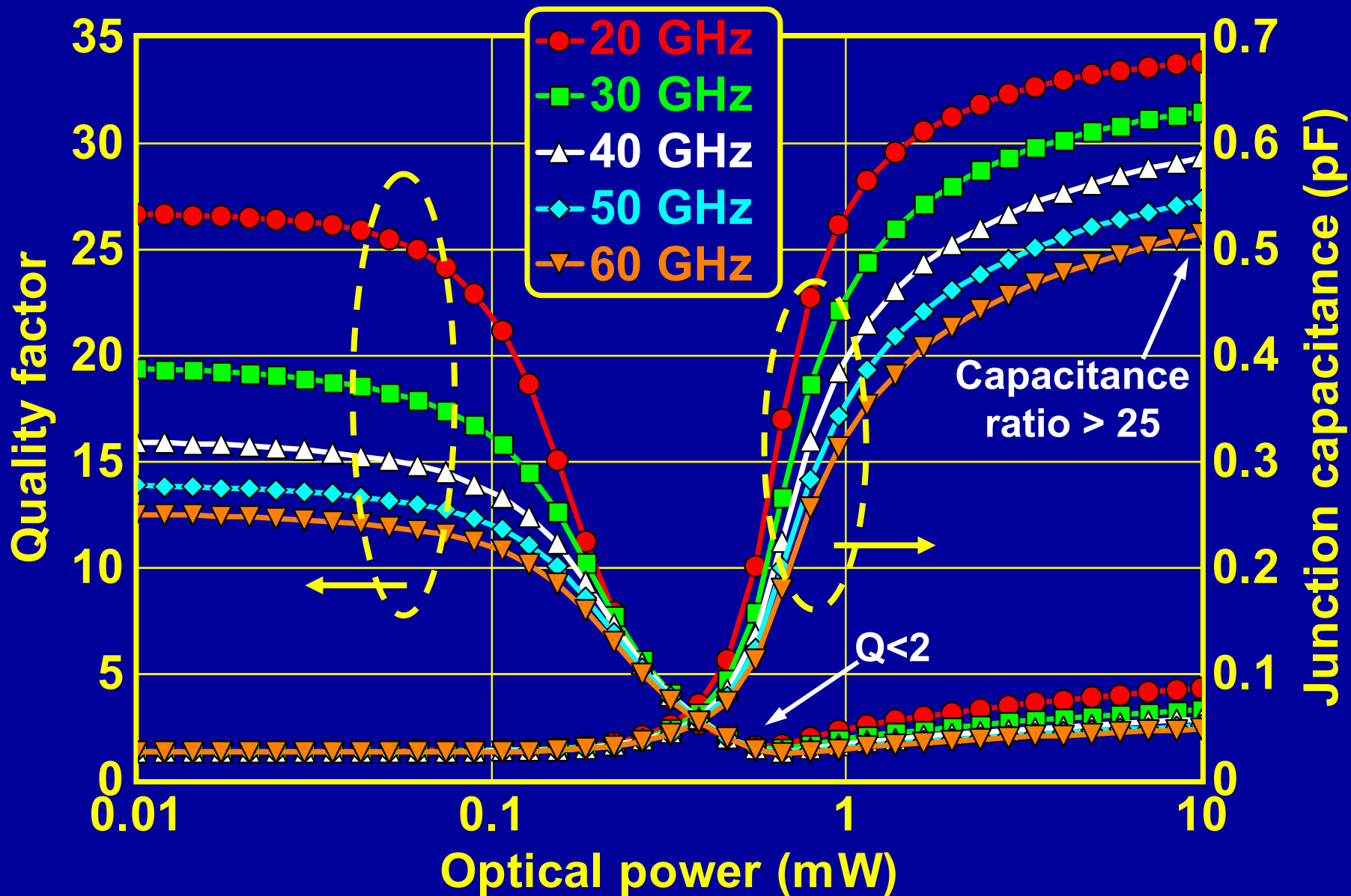
zero bias voltage,
illuminated power 0÷4mW
at the 1.55 μm wavelength

Photovaractor principle

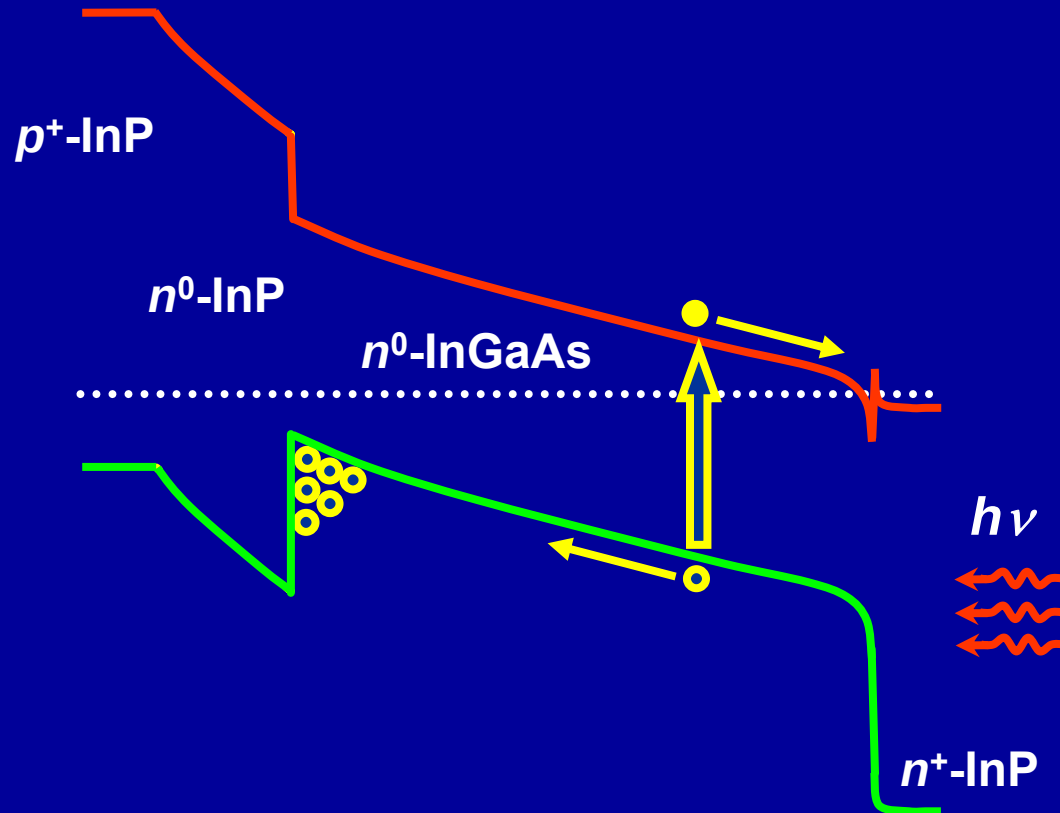
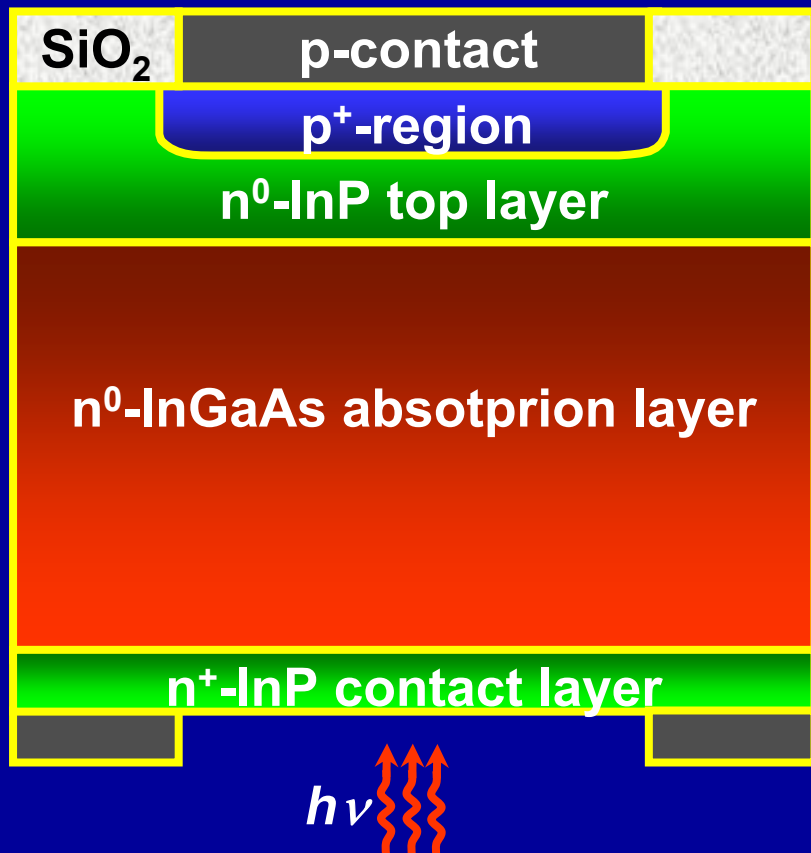
35 μm -diameter, zero bias voltage



Simulated capacitance & quality factor of 15 μ m-diameter InGaAs/InP p-i-n photovaractor (absorption i-layer thickness – 1 μ m)

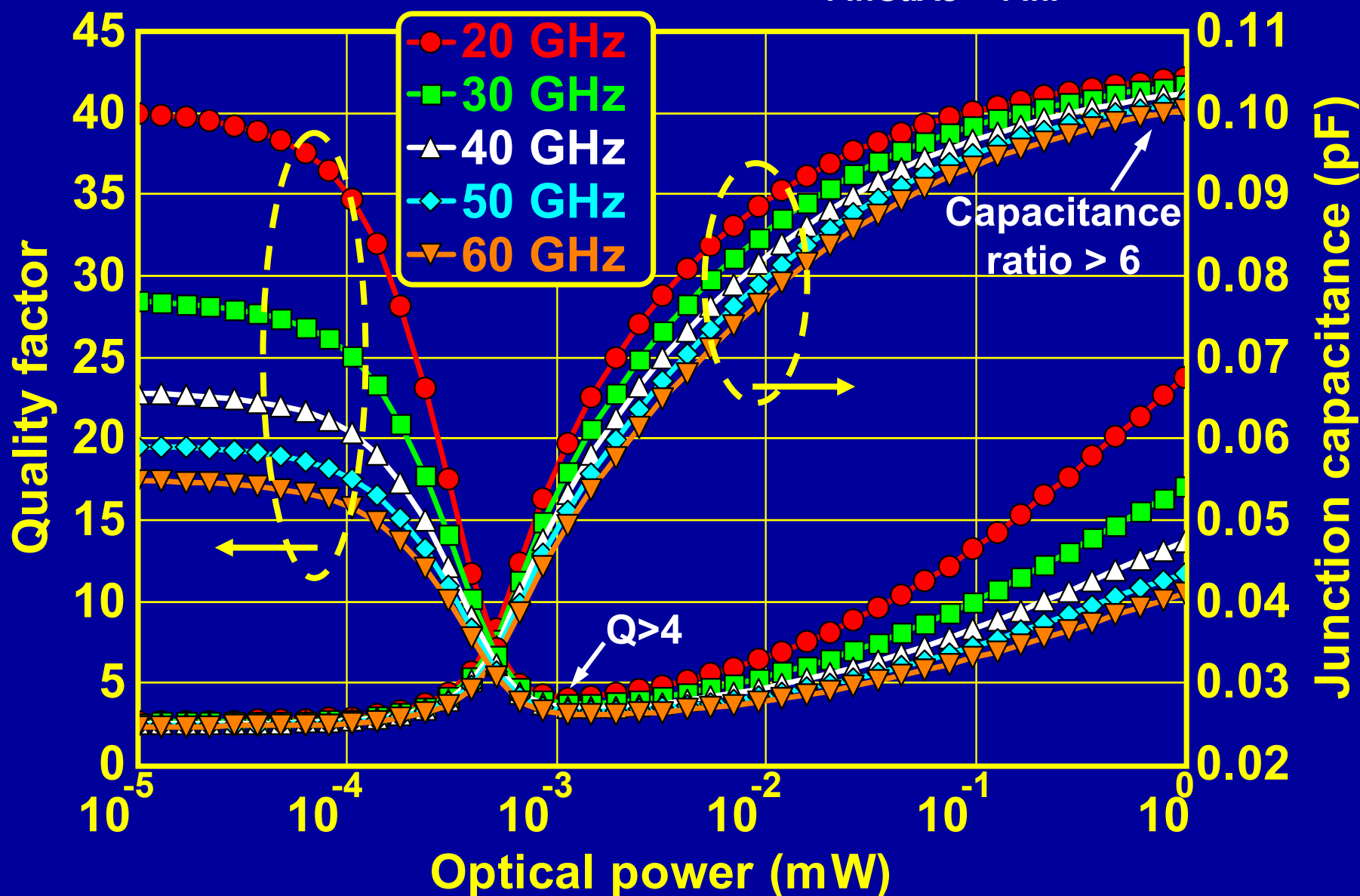


Dual-depletion region InGaAs/InP p-i-n photovaractor

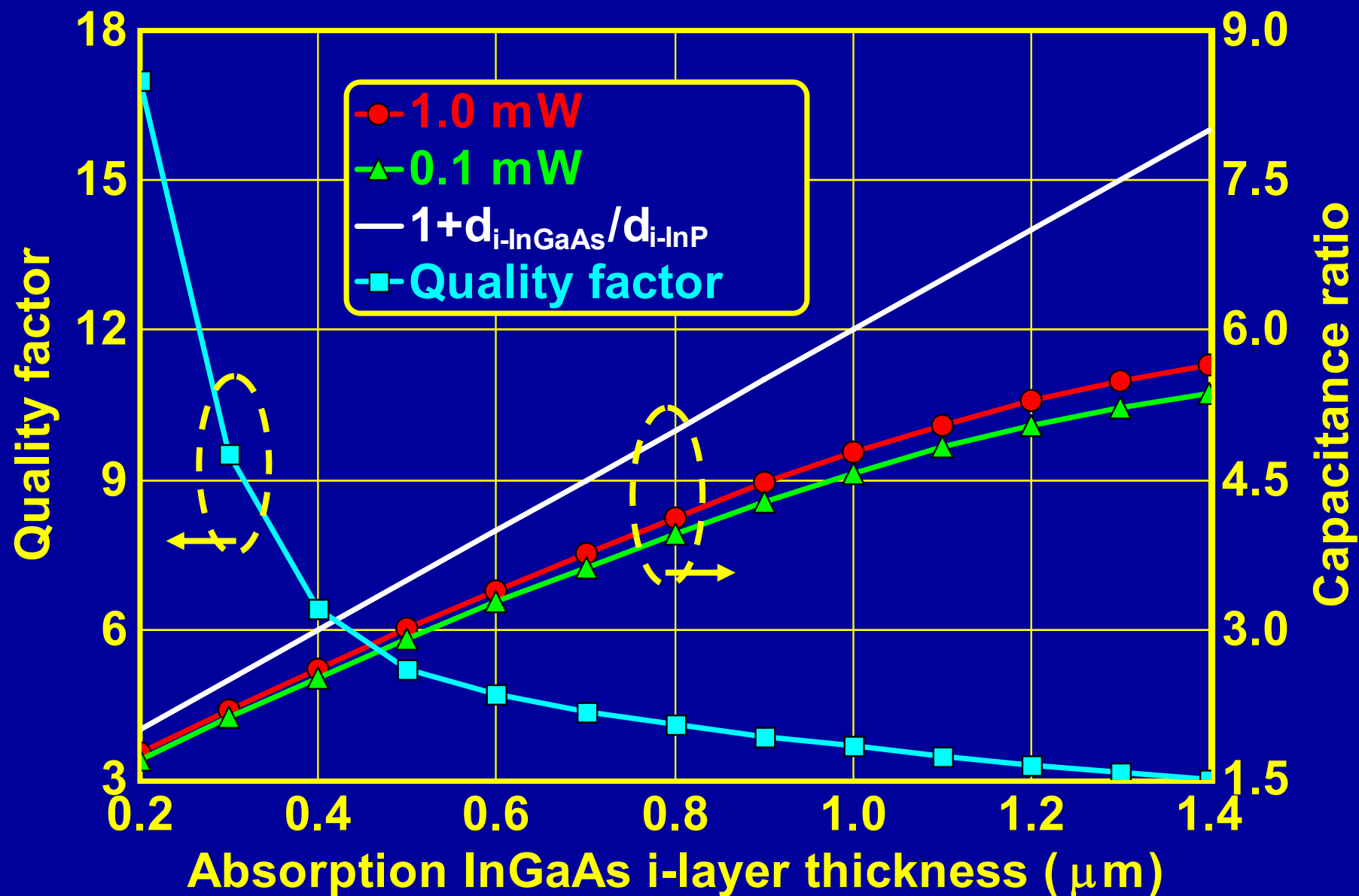


$$C_{\max} / C_{\min} = 1 + d_{\text{i-InGaAs}} / d_{\text{i-InP}}$$

Simulated capacitance & quality factor of
15 μm -diameter InGaAs/InP DDR p-i-n photovaractor
(i-layer thickness = 1 μm , $d_{\text{i-InGaAs}}/d_{\text{i-InP}} = 4$)

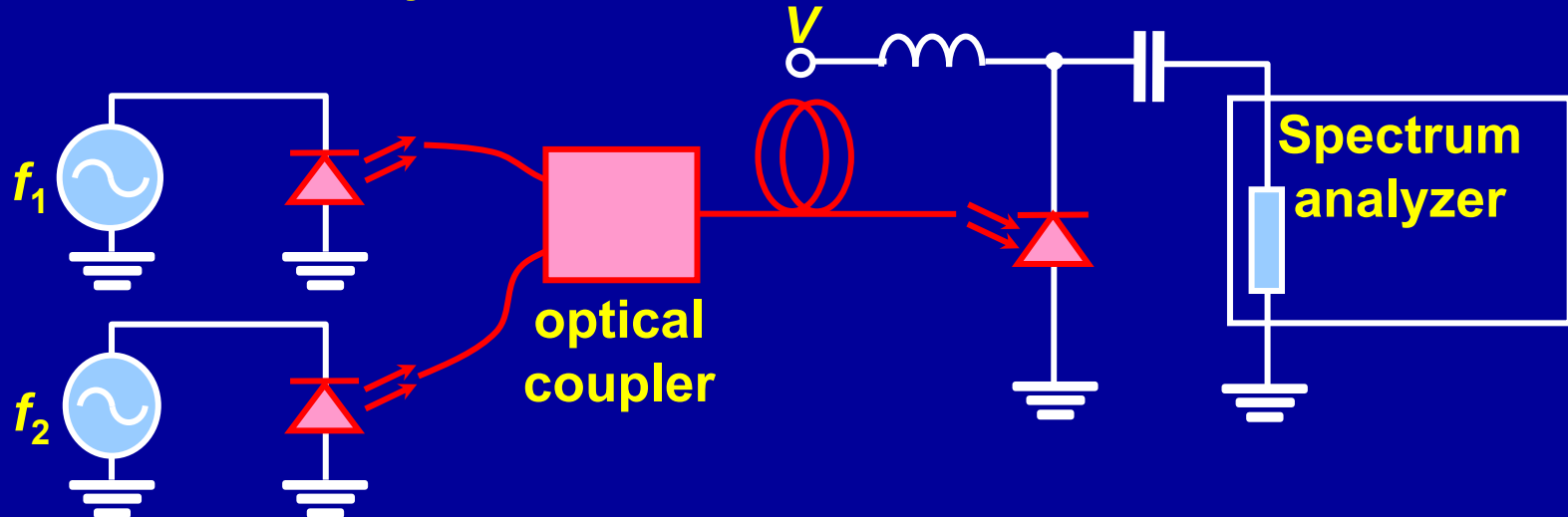


Simulated capacitance ratio & quality factor of
15 μm -diameter InGaAs/InP DDR p-i-n photovaractor
(i-InP layer thickness 0.2 μm)

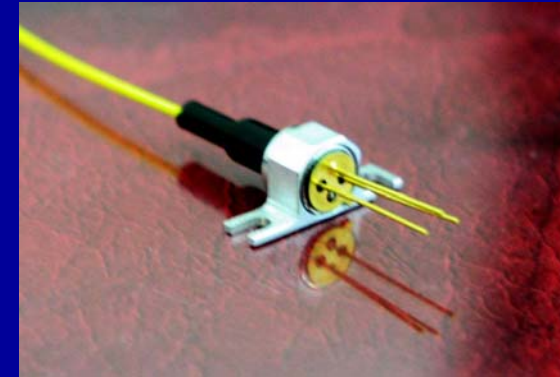
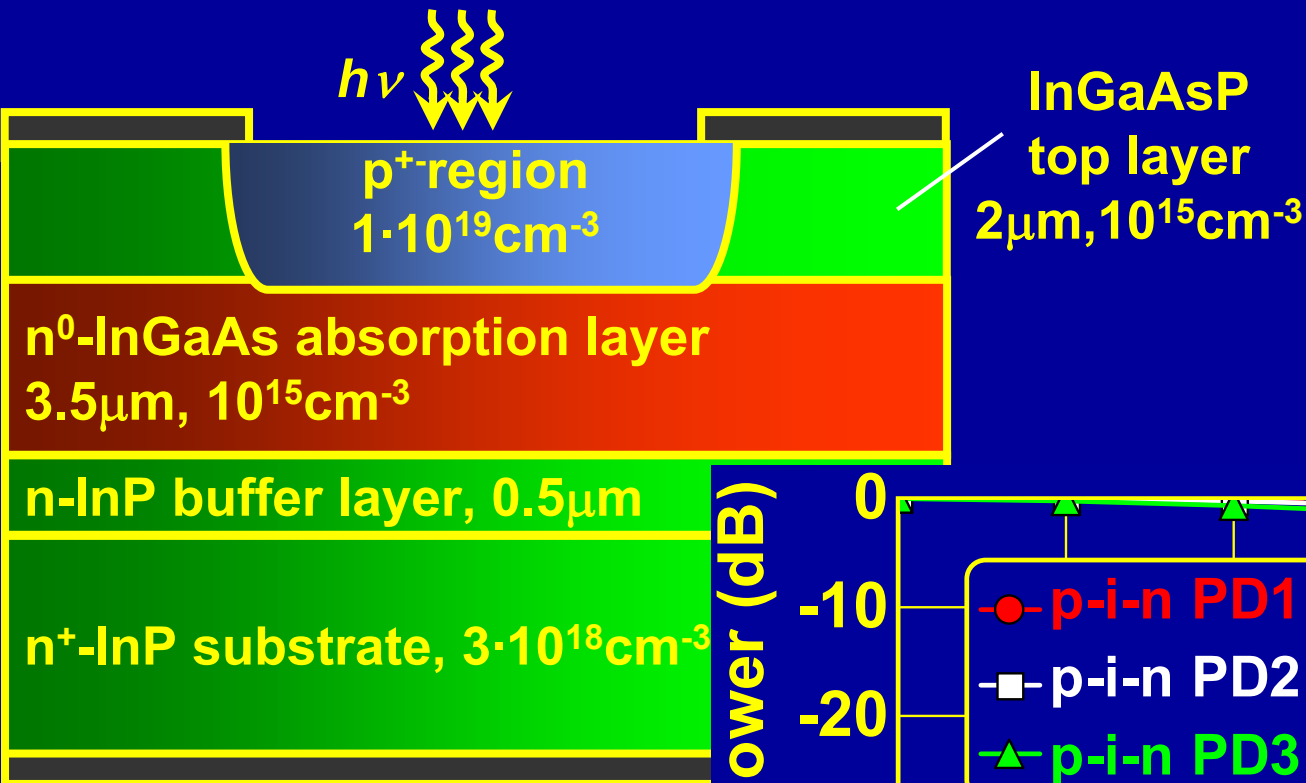


Simulation example: optoelectronic mixer

- The recovering process of an electrical signal in fiber-optic systems can be simplified by using optoelectronic mixing phenomena in photodiode between optically transmitted microwave signals
- In this technique
 - the photodiode fulfils the part of a detector and an up or down converter simultaneously
 - It is not required a microwave local oscillator at the receiver part
- Optoelectronic mixers based on p-i-n photodiodes offer potentially high-performance alternatives for
 - subcarrier-multiplexed fiber-optical systems
 - radio-on-fiber systems



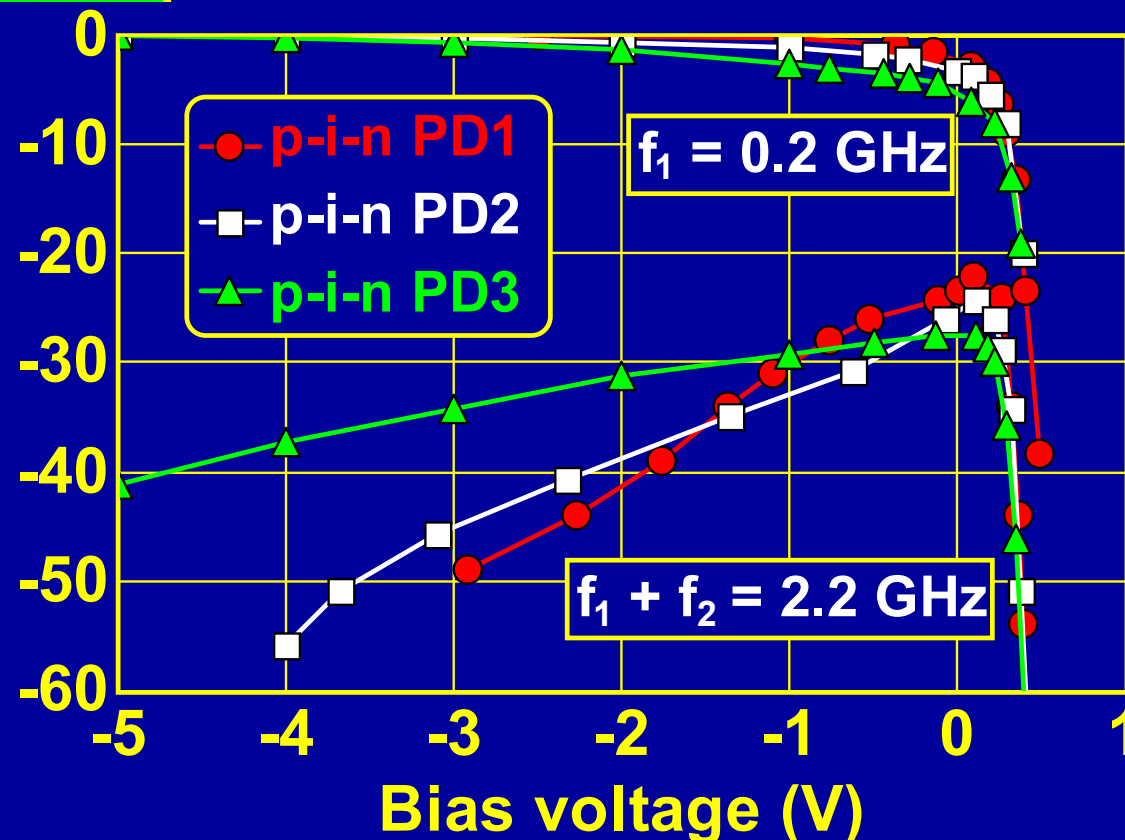
30μm-diameter p-i-n optoelectronic mixer



Different p-n junction depth:

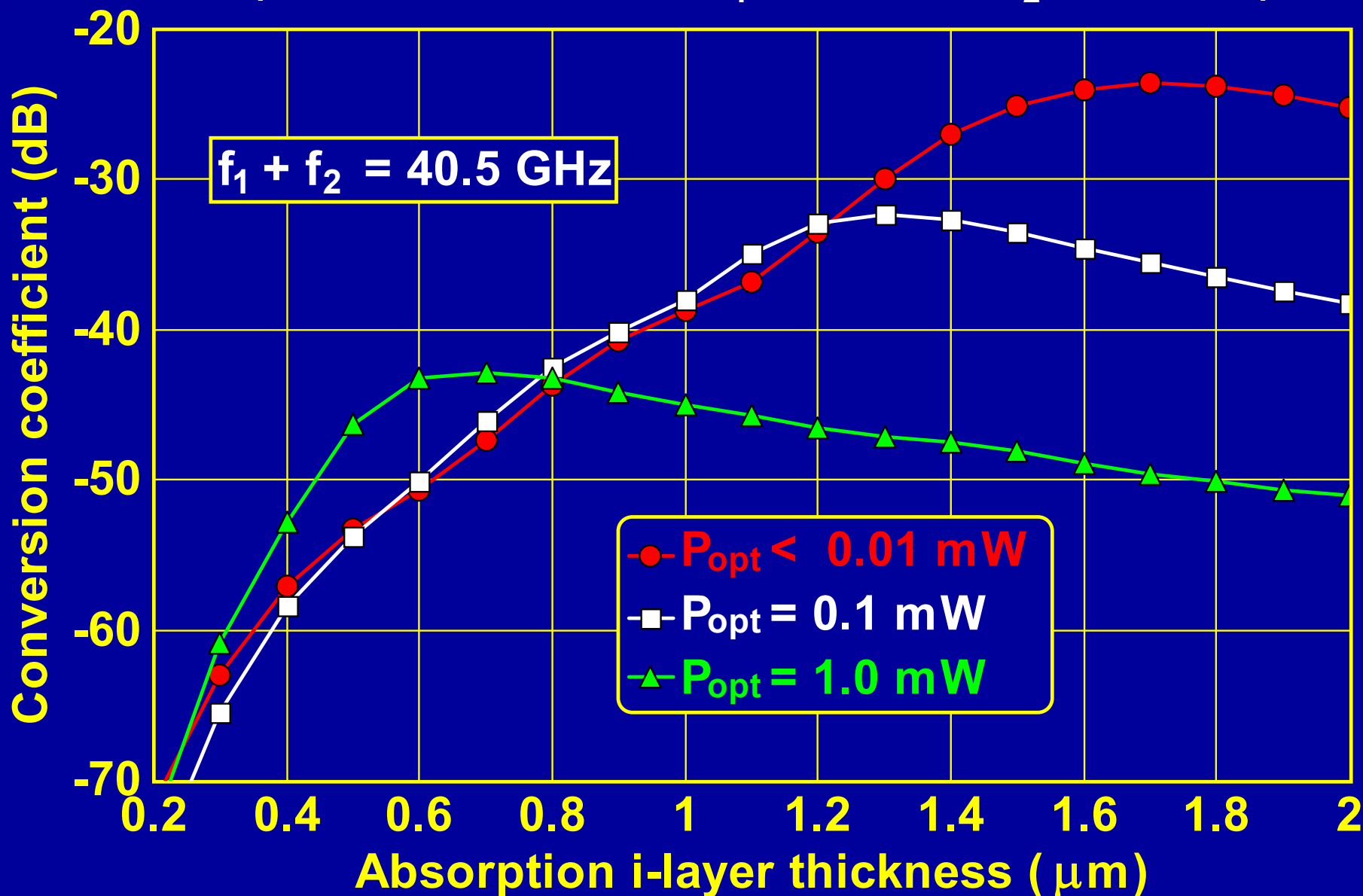
- p-i-n PD1 – 2.2 μm
- p-i-n PD2 – 2.0 μm
- p-i-n PD3 – 1.8 μm

Microwave power (dB)



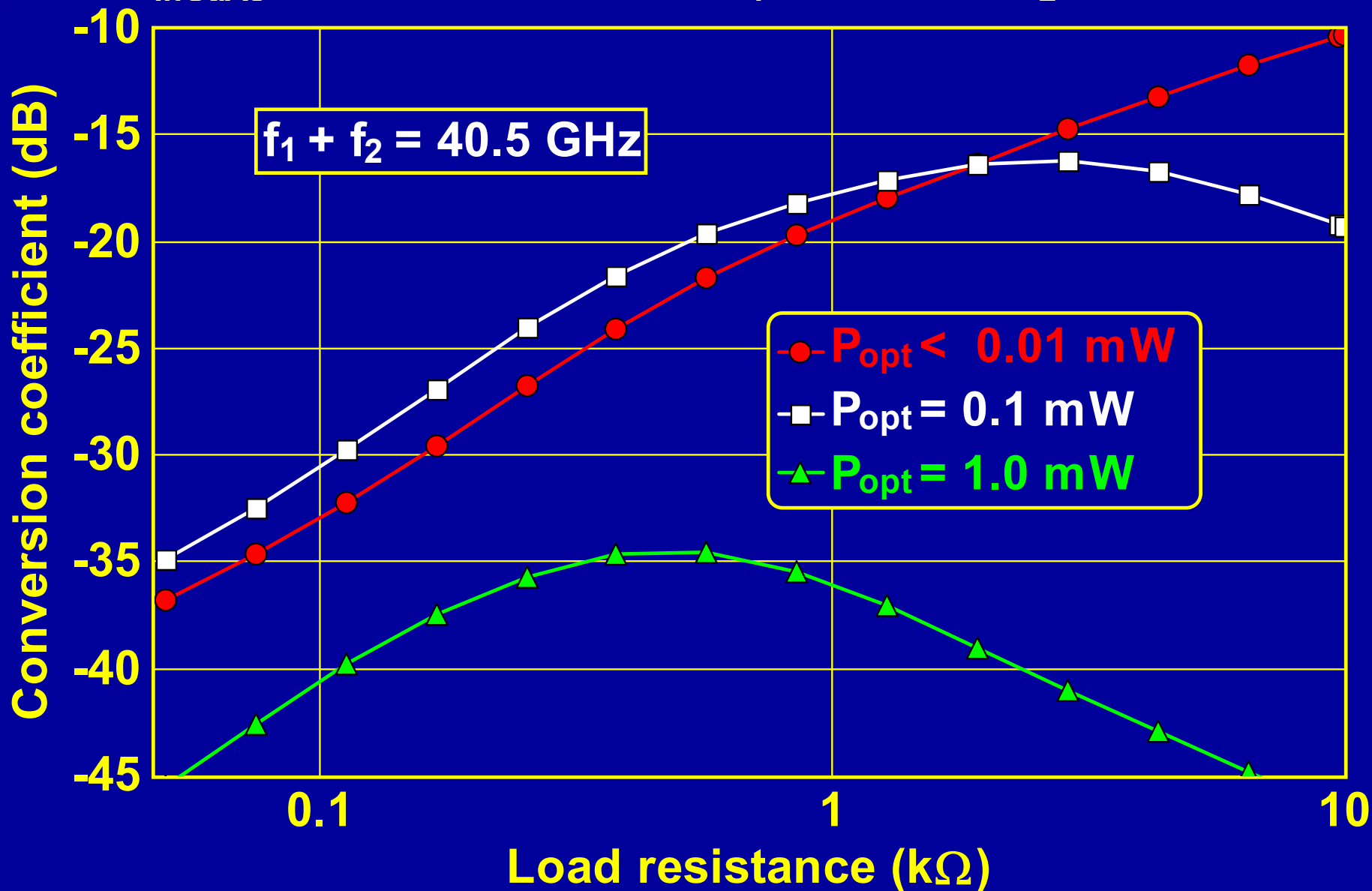
$$P_{f_1 \pm f_2} = \theta_{mix} M_1^2 P_{opt1}^2 M_2^2 P_{opt2}^2$$

Simulated conversion coefficient θ_{mix} of 10 μm -diameter
p-i-n InGaAs/InP optoelectronic up-converter
(zero bias, $Z = 50\ \Omega$, $f_1 = 0.5\ \text{GHz}$, $f_2 = 40\ \text{GHz}$)

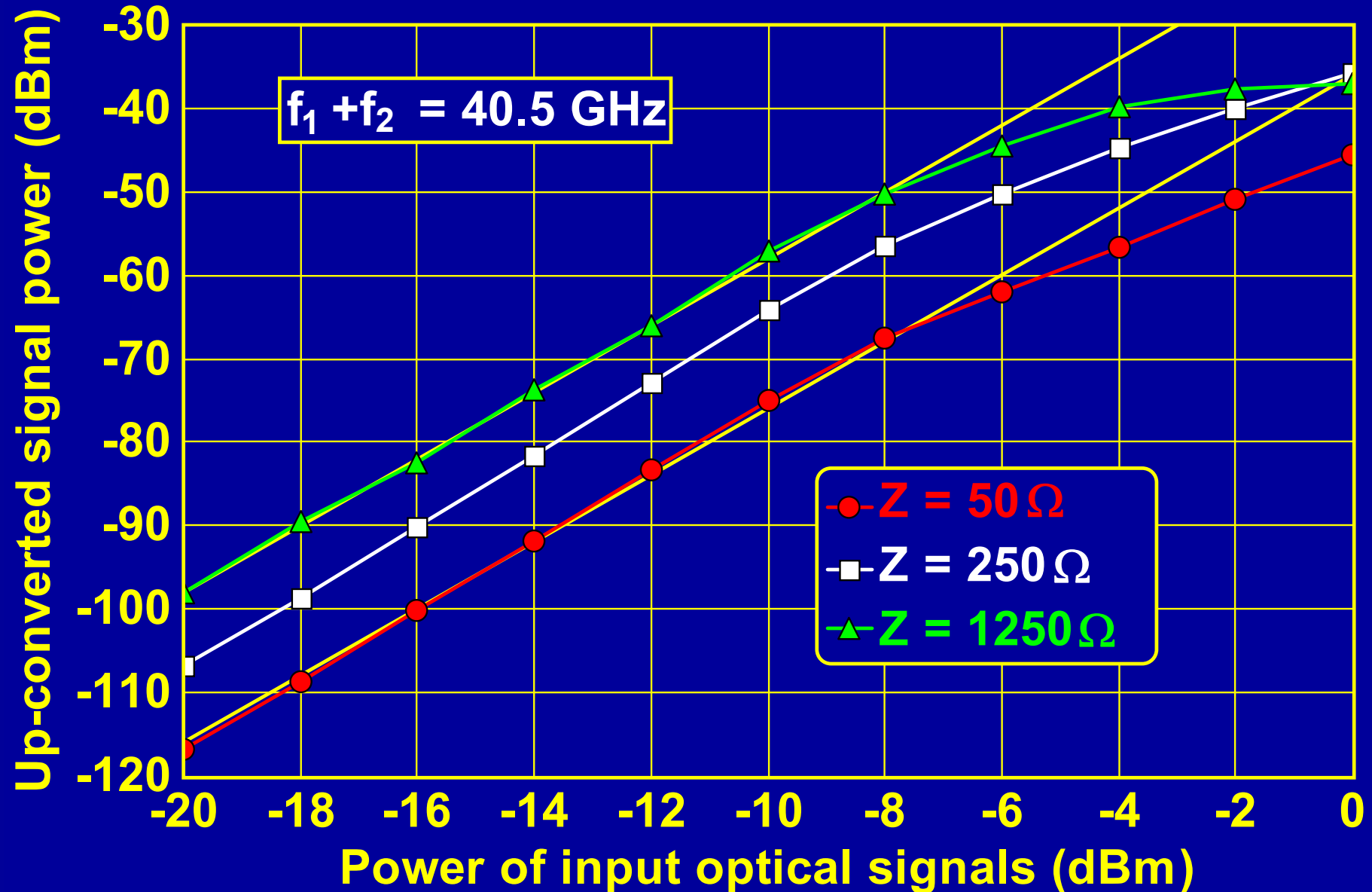


Simulated conversion coefficient θ_{mix} of 10 μm -diameter p-i-n InGaAs/InP optoelectronic up-converter

($d_{\text{InGaAs}} = 1.1 \mu\text{m}$, zero bias, $f_1 = 0.5 \text{ GHz}$, $f_2 = 40 \text{ GHz}$)



Simulated up-converted signal power at 40.5 GHz for
10 μm -diameter p-i-n InGaAs/InP optoelectronic up-converter
($d_{\text{InGaAs}} = 1.1 \mu\text{m}$, zero bias, $f_1 = 0.5 \text{ GHz}$, $f_2 = 40 \text{ GHz}$)



Conclusions

- **Mixed device/circuit model of the high-speed p-i-n photodiode has been presented**
- **The model is capable of simulation both in time and frequency domain**
- **The model is suitable for photodiode design optimization in such application as**
 - **optical control of microwave circuits**
 - **frequency conversion of optically-transmitted microwave signals**
 - **photonic generation of microwaves**
 - **optical signal detection**