

New Materials and Devices for Pushing Present Speed Barriers

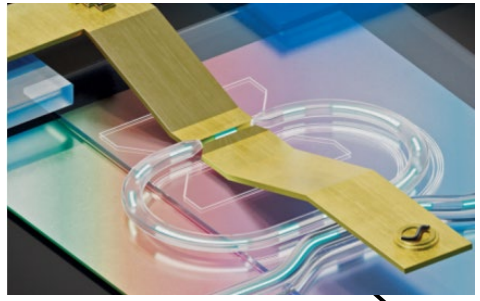
Juerg Leuthold[1], Tobis Blatter[1], Stefan M. Koepfli, Xinzhi Zhang, Michael Baumann, Shadi Nashashibi, Marina Homs, Jasmin Smajic, Yuriy Fedoryshyn,…

(1) ETH Zurich, Institute of Electromagnetic Fields (IEF), 8092 Zürich, Switzerland,

The Big Picture

Developing the critical components to enable operation at any frequency up to 500 GHz and beyond.

Modulators, Phased Arrays



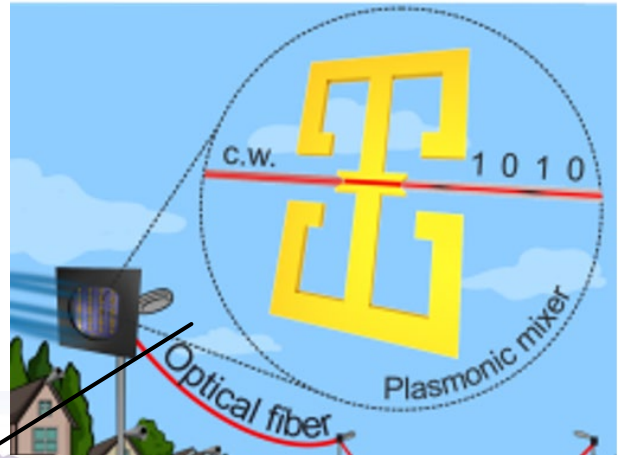
M. Eppenberger et al, Nature Photonics 2023

Fast & Efficient Photodiodes

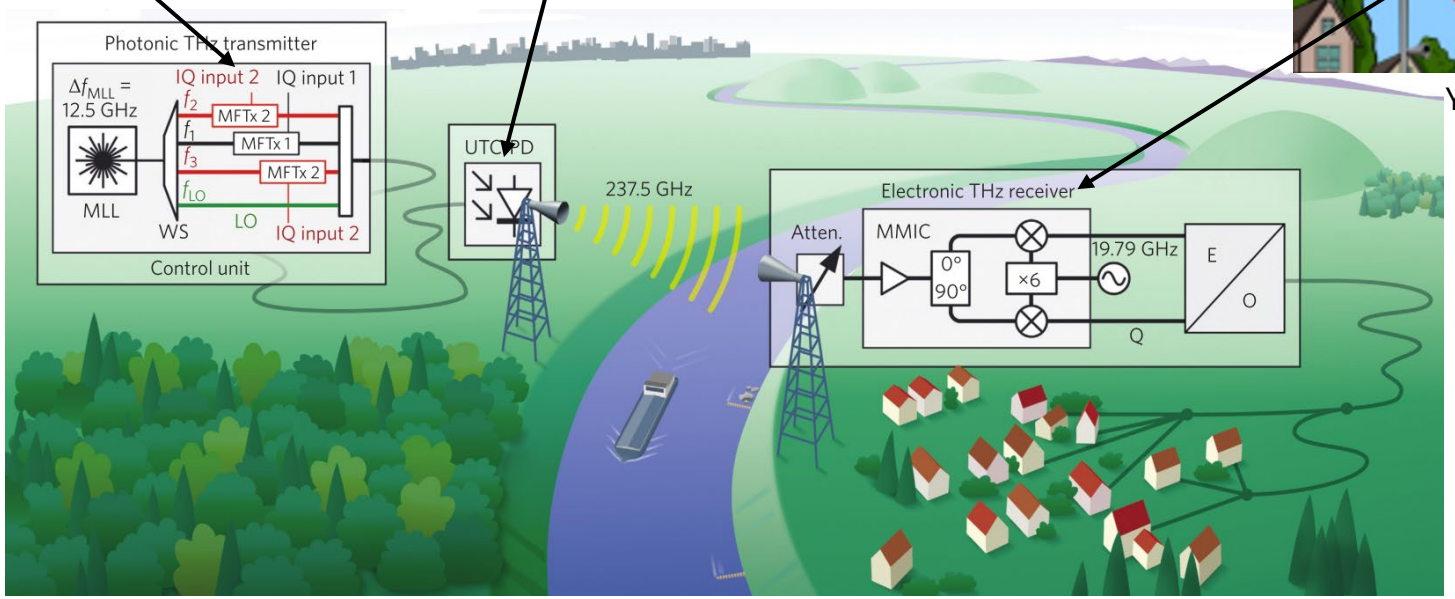


S. Köpfli et al; Science 2023

THz Antenna



Y. Salamin *et al., Nature Photonics, Dec. 2018*

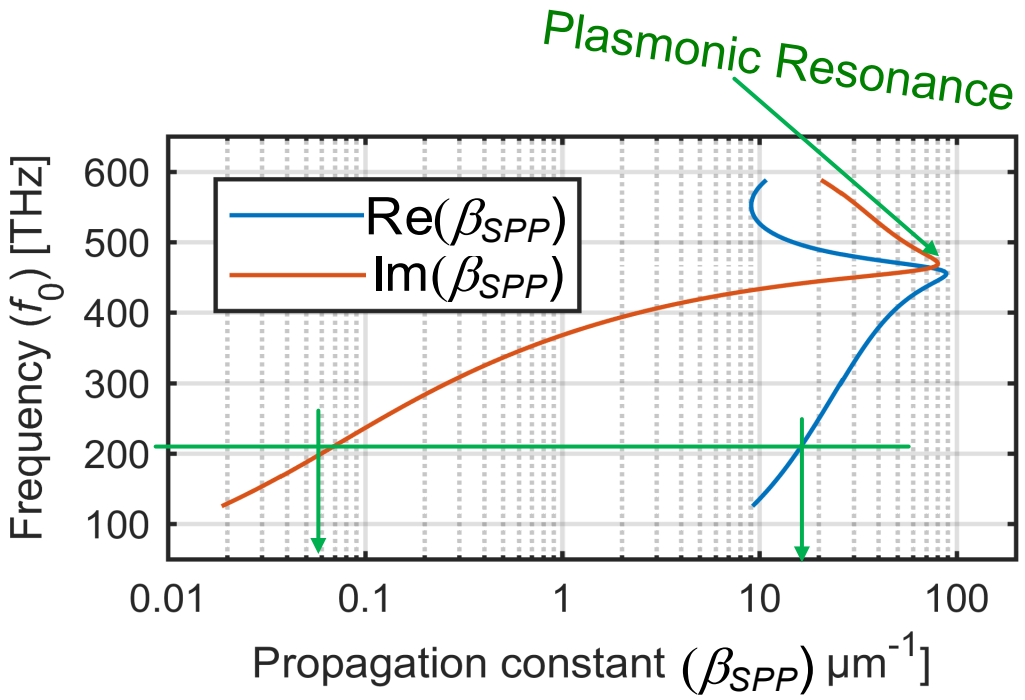


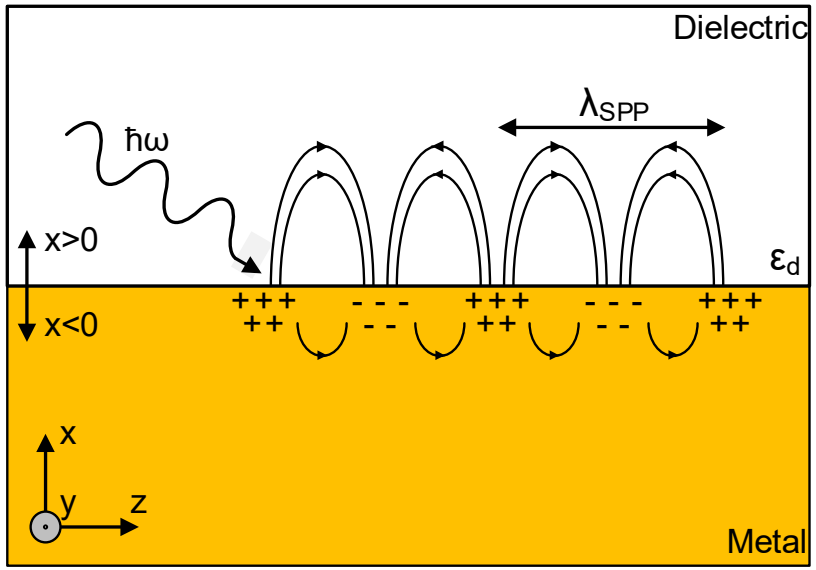
S. Koenig *et al., Nature Photonics, Dec. 2013,*

Plasmonics – Surface Plasmon Polaritons (SPP)

$$\beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}$$ with ε for gold and Si

where β is the propagation constant: $e^{-j\beta z}$





$$\lambda_{spp} = \frac{2\pi}{\beta'}$$

Plasmonic wavelength much smaller than in photonics
→ Small Size
→ Coupling is difficult (Phase-Mismatch)

$$L_{spp} = \frac{1}{2\beta''}$$

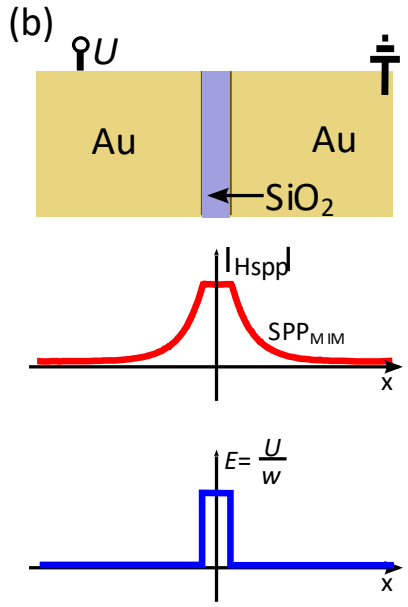
Strong attenuation
→ After a few μm all of the light is absorbed

Content

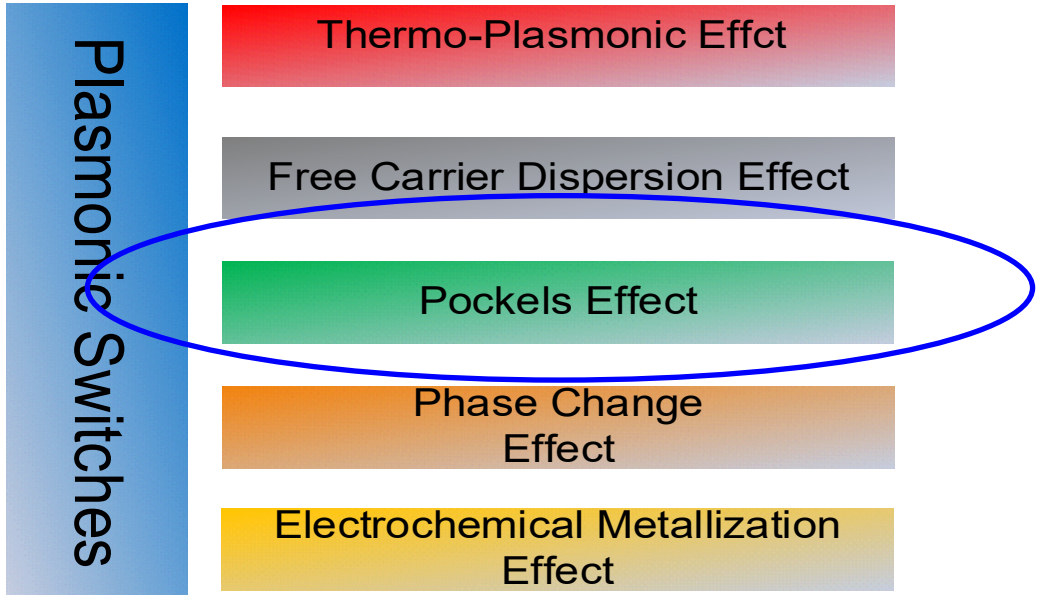
- Modulators
- Detectors

Plasmonic Modulator – The Linear Electro-Optic Effect

Highly lossy plasmonic waveguide
– but compact



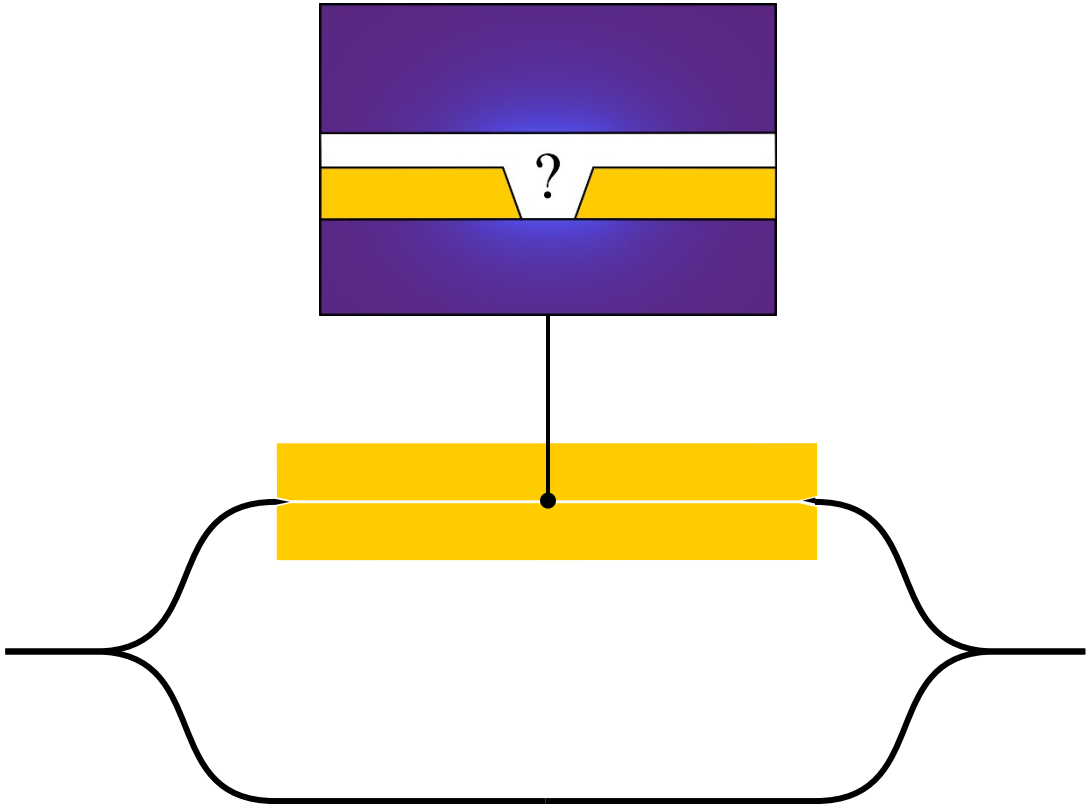
Inefficient Pockels-Effect
- but fast



Idea: Combine the worst of two worlds
to get a compact and ultra-fast device!

A. Emboras, C. Hoessbacher, C. Haffner, W. Heni, U. Koch, M. Ping, Y. Fedoryshyn, J. Niegemann, C. Hafner, and J. Leuthold, "Electrically controlled plasmonic switches and modulators," IEEE Journal of Selected Topics in Quantum Electronics (JSTQE) **(2015).**

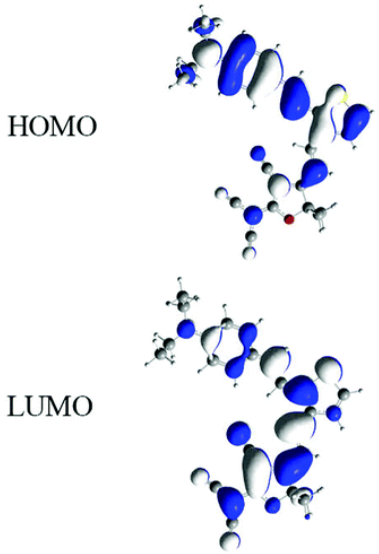
Nonlinear Materials



Organic Molecules

+ r ~ 100-1000 pm/V

– Heat Sensitive

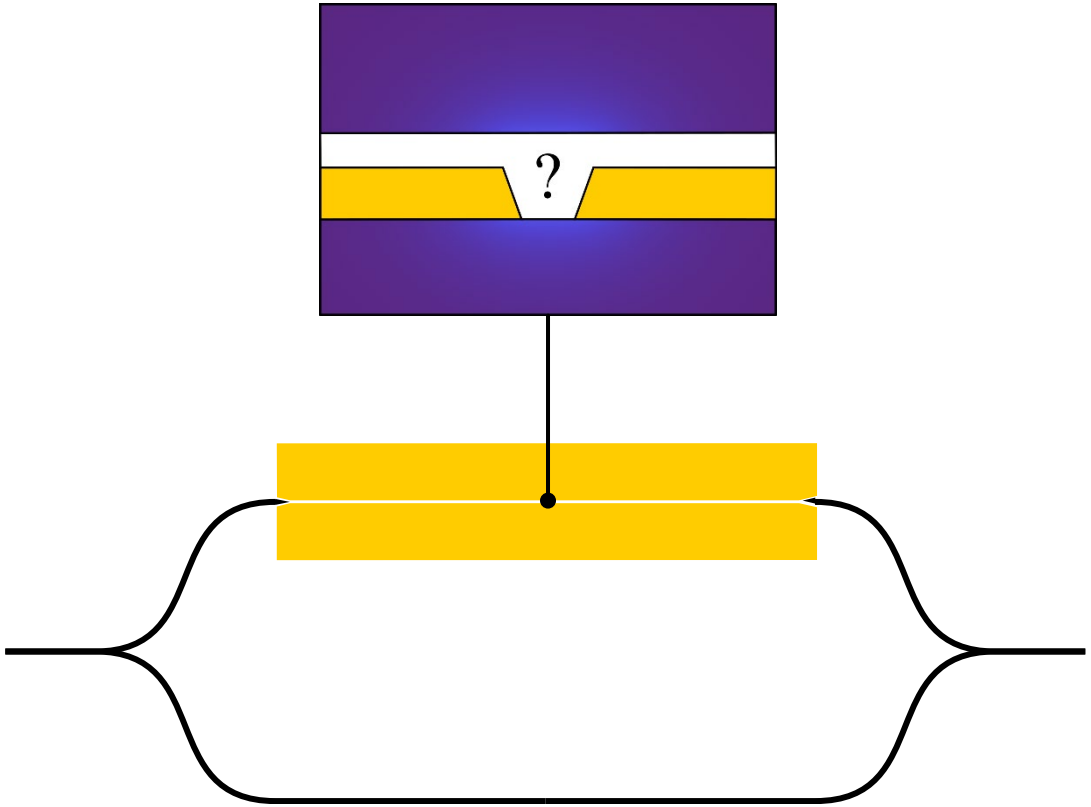


https://doi.org/10.1364/AOP.411024

https://doi.org/10.1039/C9TC05704H

Ref.: H. Xu, D. L. Elder, L. E. Johnson, Y. de Coene, W. Heni, D. Moor, S. R. Hammond, K. M. O'Malley, K. Clays, J. Leuthold, L. R. Dalton, and B. H. Robinson, "Ultrahigh Performance Cross-Linkable Organic Electro-Optic Material for Hybrid Modulators," Chemistry of Materials 37 (2025).

Nonlinear Materials



Organic Molecules

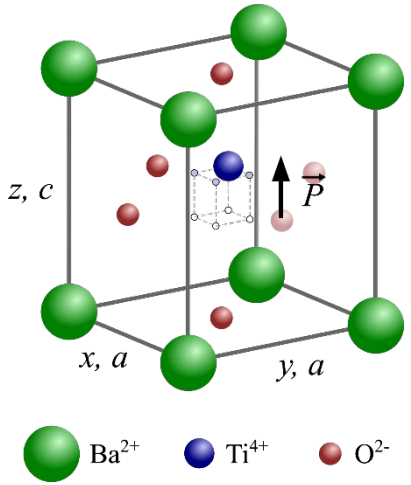
+ r ~ 100-1000 pm/V

– Heat Sensitive

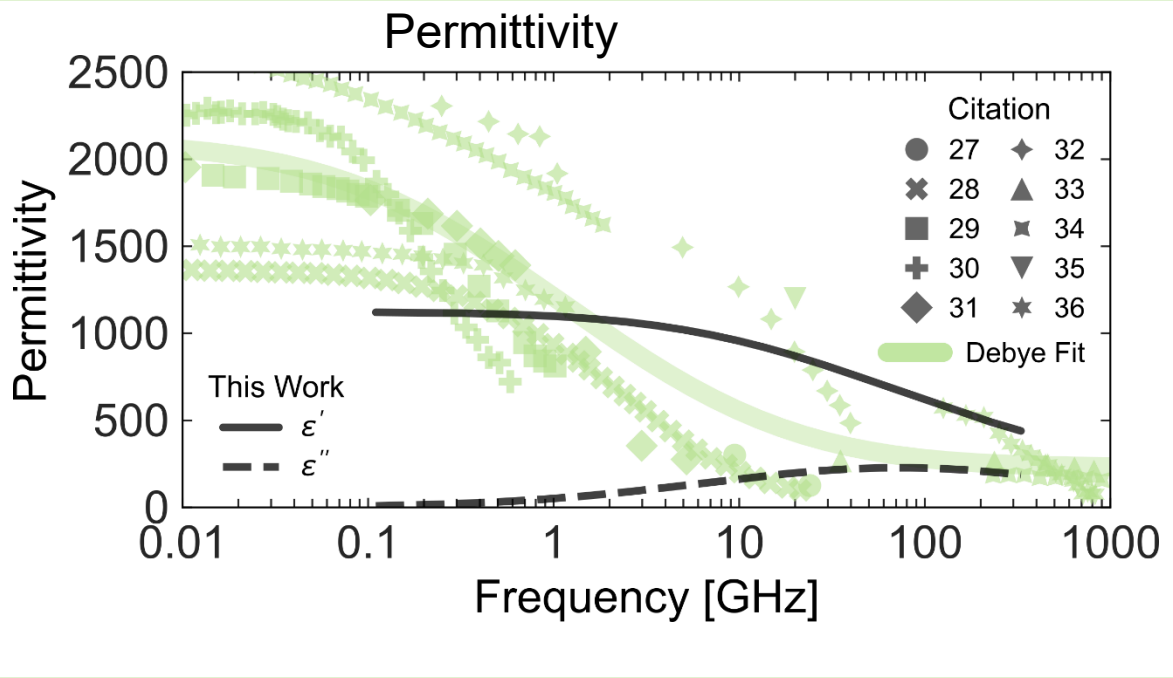
Barium Titanate

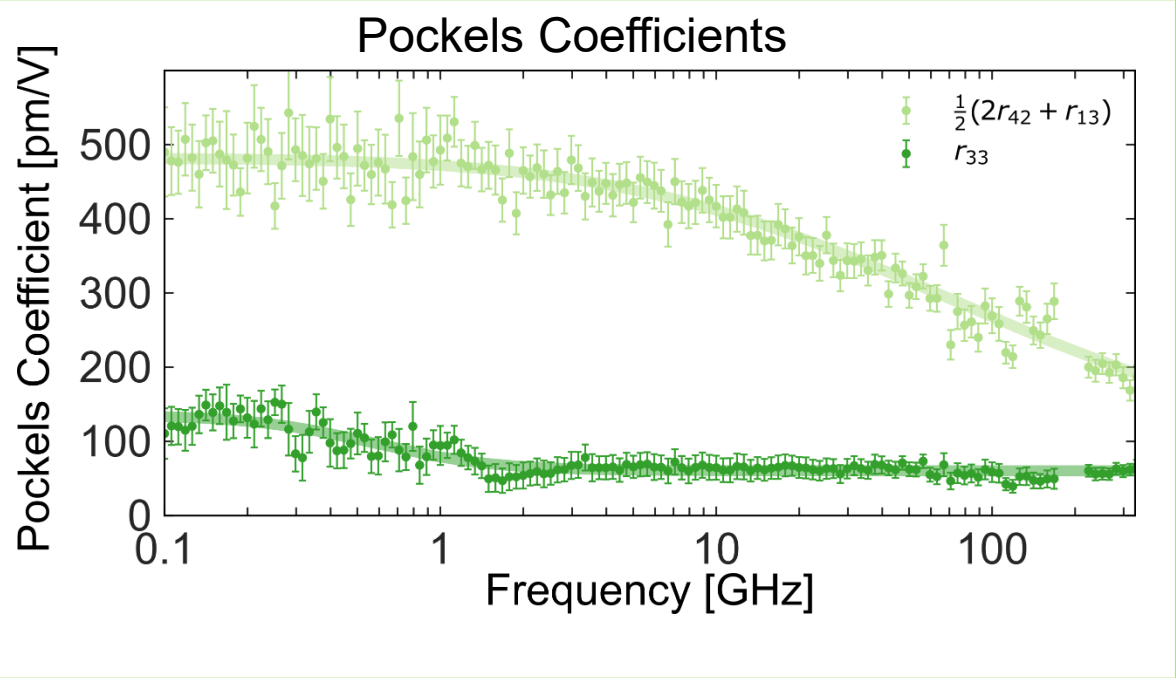
+ r ~ 1000 pm/V

+ durable



Barium Titanate – Characterized for Frequency Response



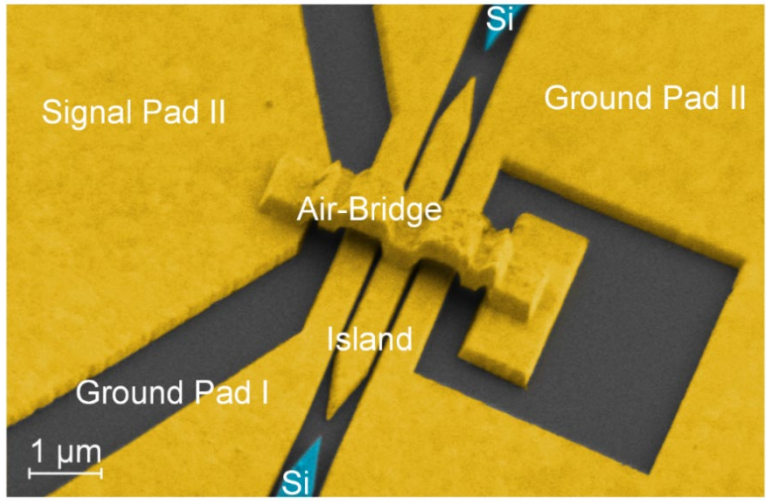


- Large spread in available data
- Purity, defects, preparation → uneven comparison
- $\varepsilon_{f=10\ \mathrm{MHz}} = 1136 \rightarrow \varepsilon_{f=330\ \mathrm{GHz}} = 453$ (Debye Model)

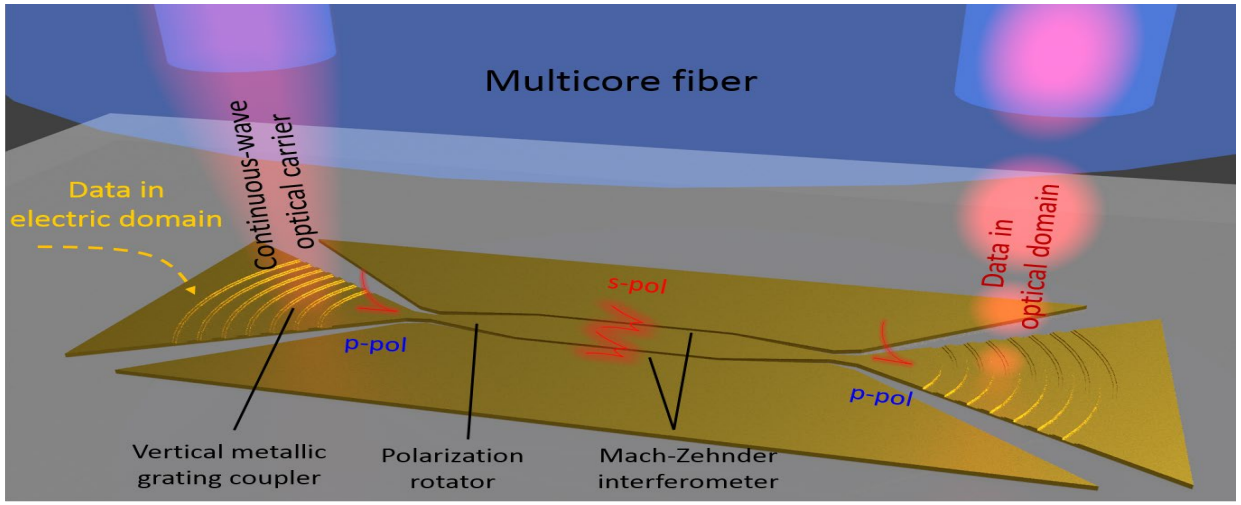
- First measurements over this continuous range
- $r_{33} = 125$ pm/V → $r_{33} = 60$ pm/V (Debye Model)
- $r_{42} \approx 481$ pm/V → $r_{42} \approx 191$ pm/V ($\delta = 0.33$ pm/V)

Ref.: D. Chelladurai, et al., "Barium Titanate and Lithium Niobate Permittivity and Pockels Coefficients from MHz to Sub-THz Frequencies," Nature Materials, 2025

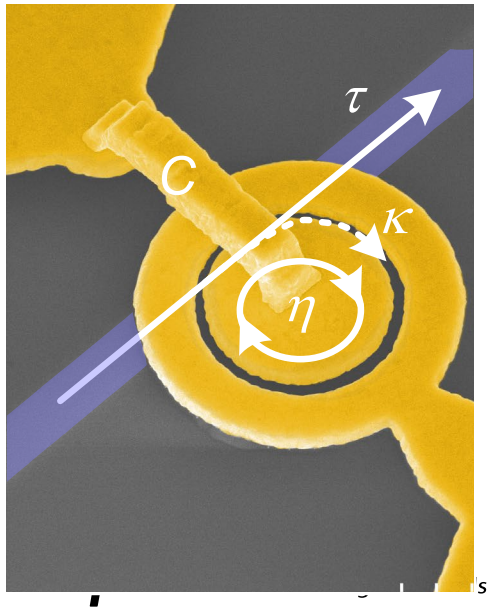
Plasmonic Modulators – the Footprint



Mach-Zehnder modulator in a waveguide: **10 µm length**, 8 dB Losses
Ref.: C. Haffner *et al., Nature Photonics, pp. 525-528, Aug. 2015.*

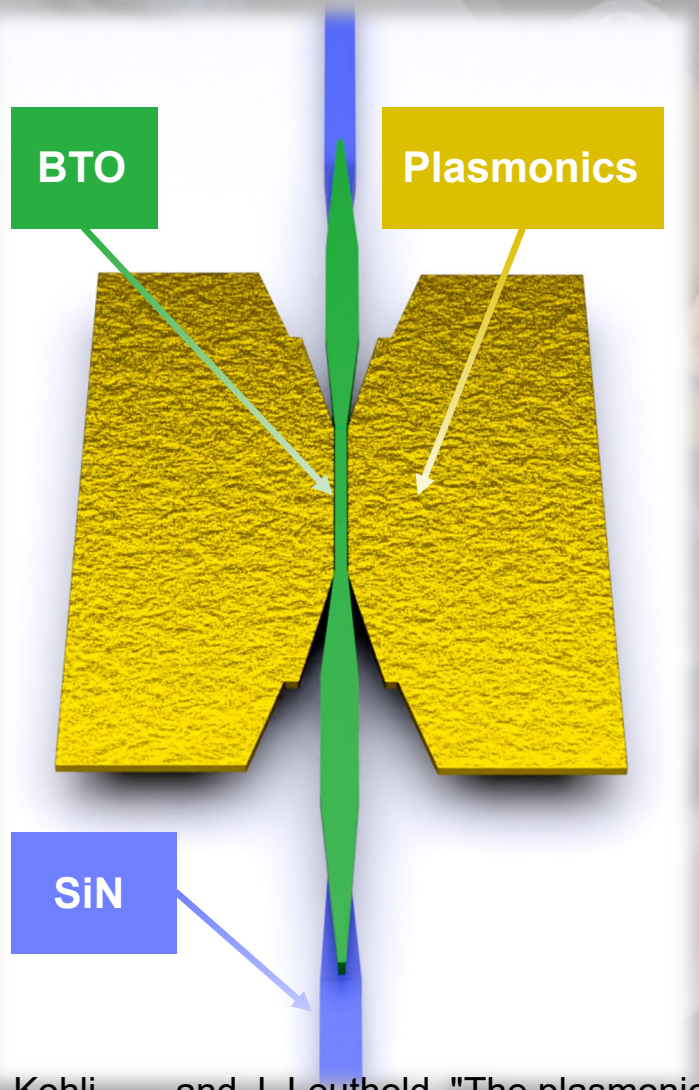


All metallic, **30 µm length**
Ref.: M. Ayata, *et al., Science, pp. 630-632, 2017.*



Ring modulator: **Radius 1.0 µm**; Device losses: 2.4 dB
Ref.: C. Haffner, *et al., "Low-loss plasmon-assisted electro-optic modulator," Nature, pp. 483-486, 2018.*

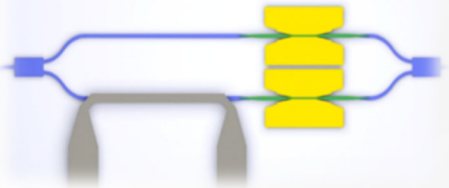
The Plasmonic BTO-on-SiN Platform

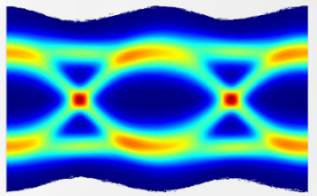


BTO-on-SiN Platform

C-Band Mach-Zehnder

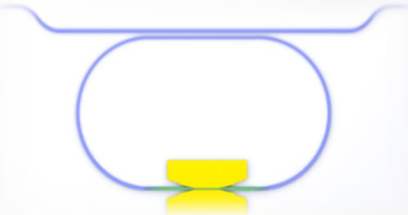
256 GBd

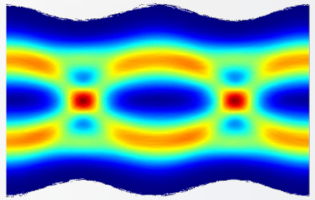




O-Band Racetrack

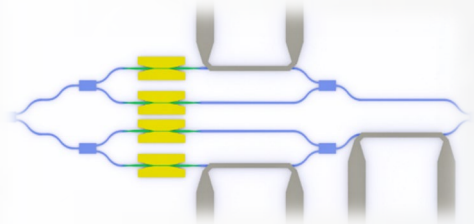
200 GBd

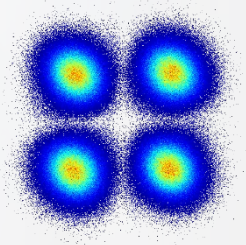




C-Band IQ

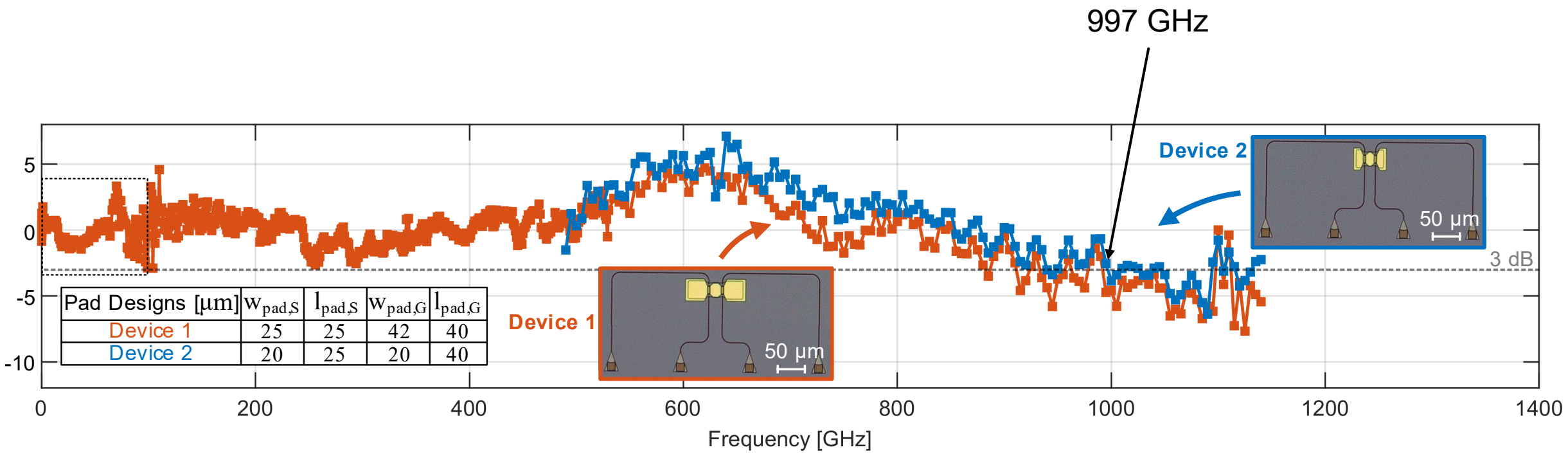
224 GBd





M. Kohli, …, and J. Leuthold, "The plasmonic BTO-on-SiN platform – beyond 200 GBd modulation for optical communications," Light: Science & Applications **14, 399 (2025).**

Plasmonic Modulators - Frequency Response

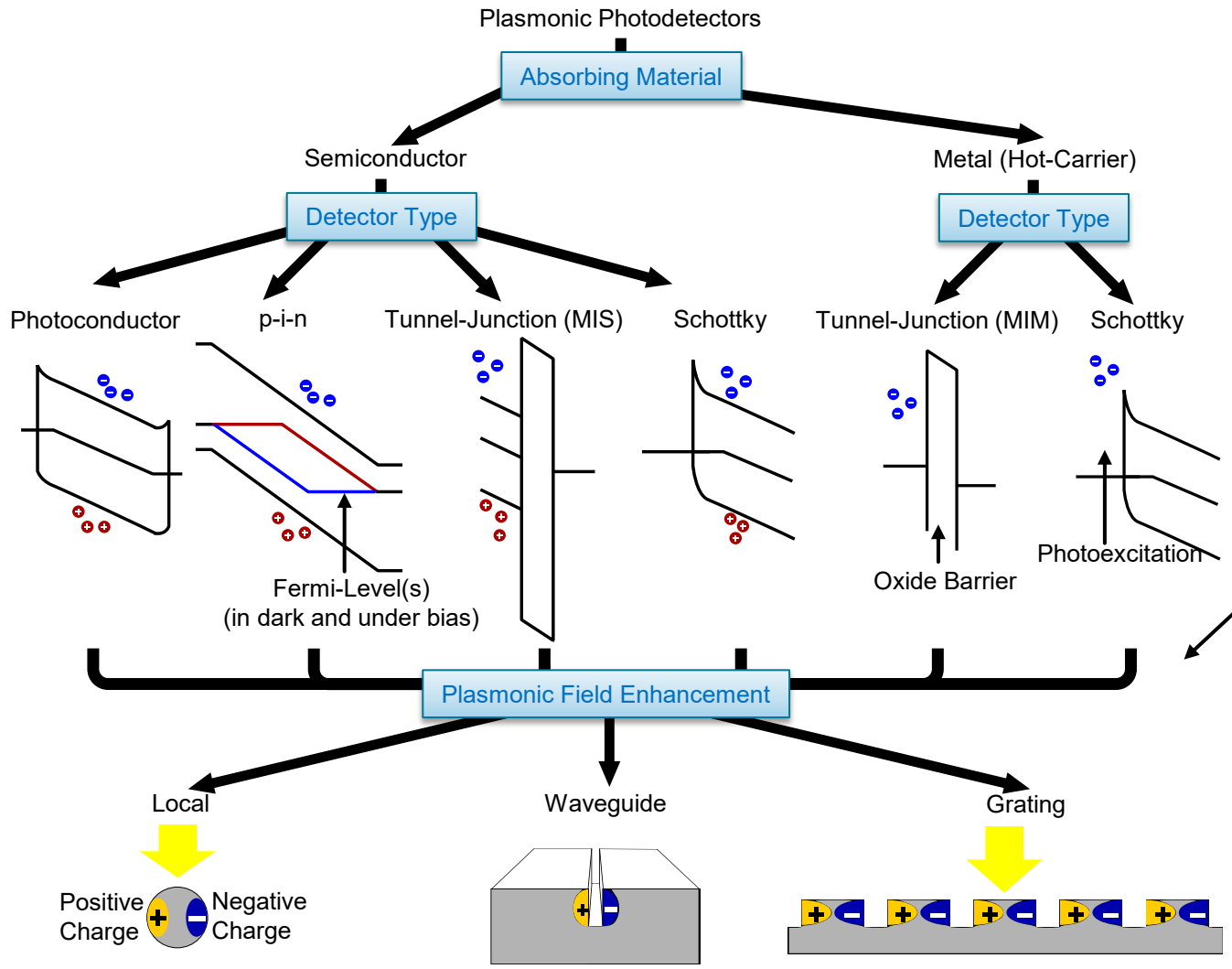


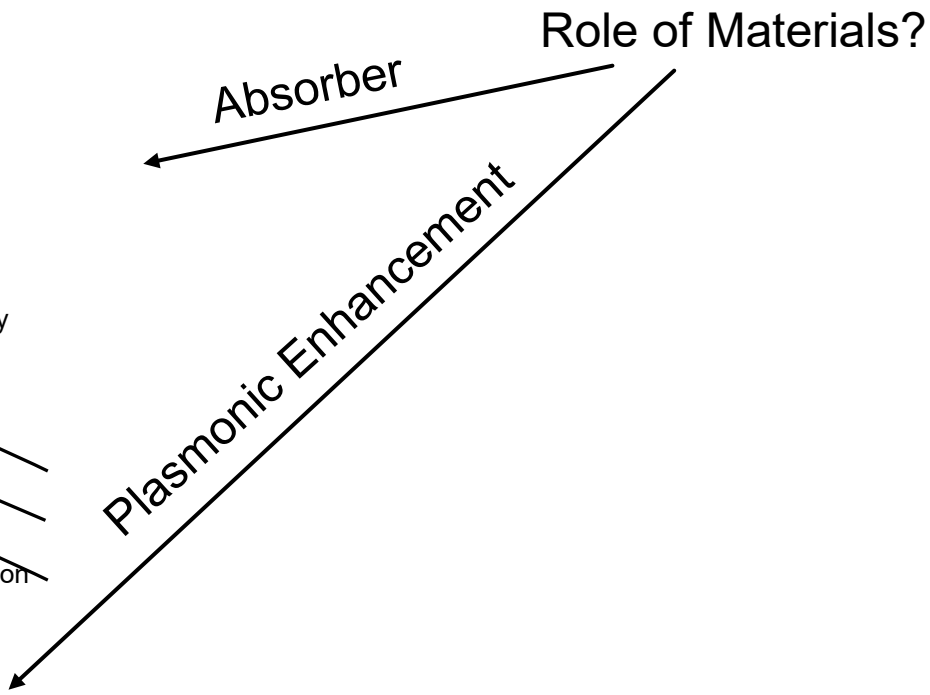
ETH & Polariton: Y. Horst, et al."Ultra-wideband MHz to THz plasmonic EO modulator," Optica 12, 325-328 (March 2025).

Content

- Modulators
- Detectors

Plasmonic Photodetectors



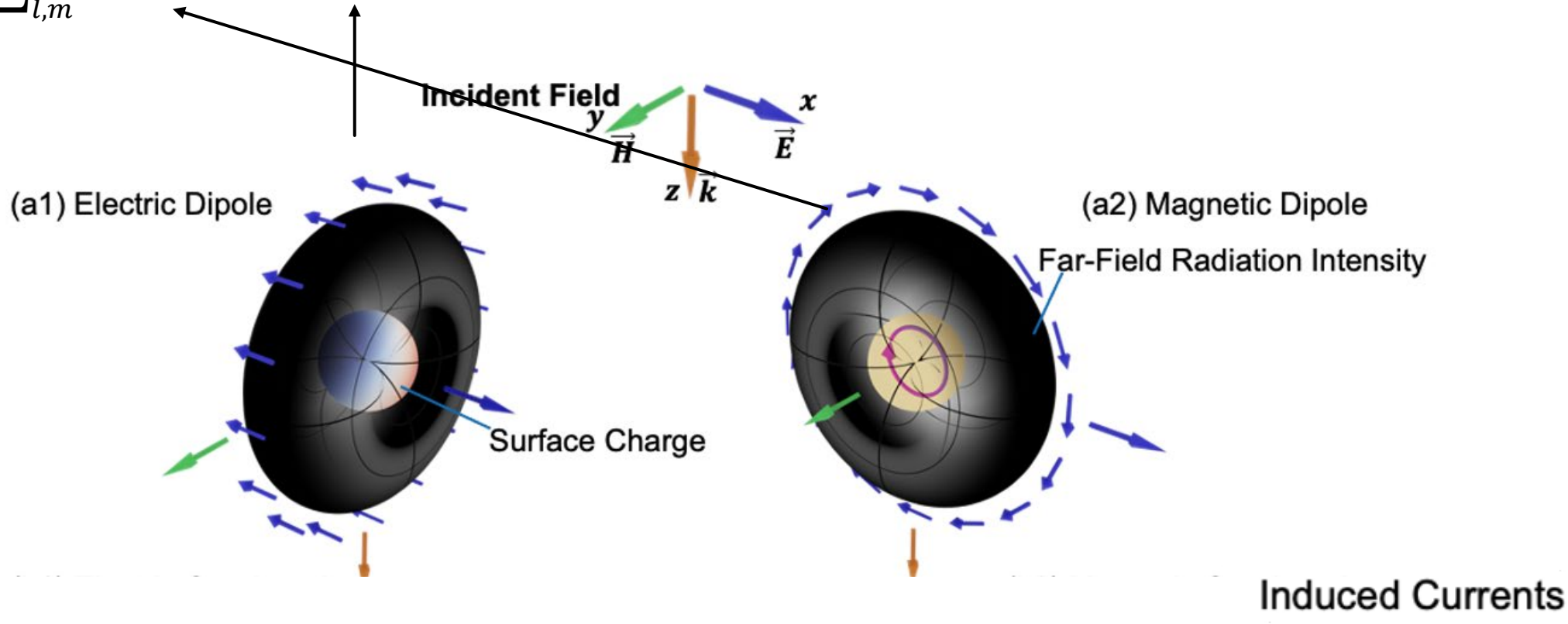


A. Dorodnyy et al., "Plasmonic Photodetectors," IEEE Journal of Selected Topics in Quantum Electronics 24, 4600313 (2018).

Plasmonic Mie Scatterer – Dipole Solution

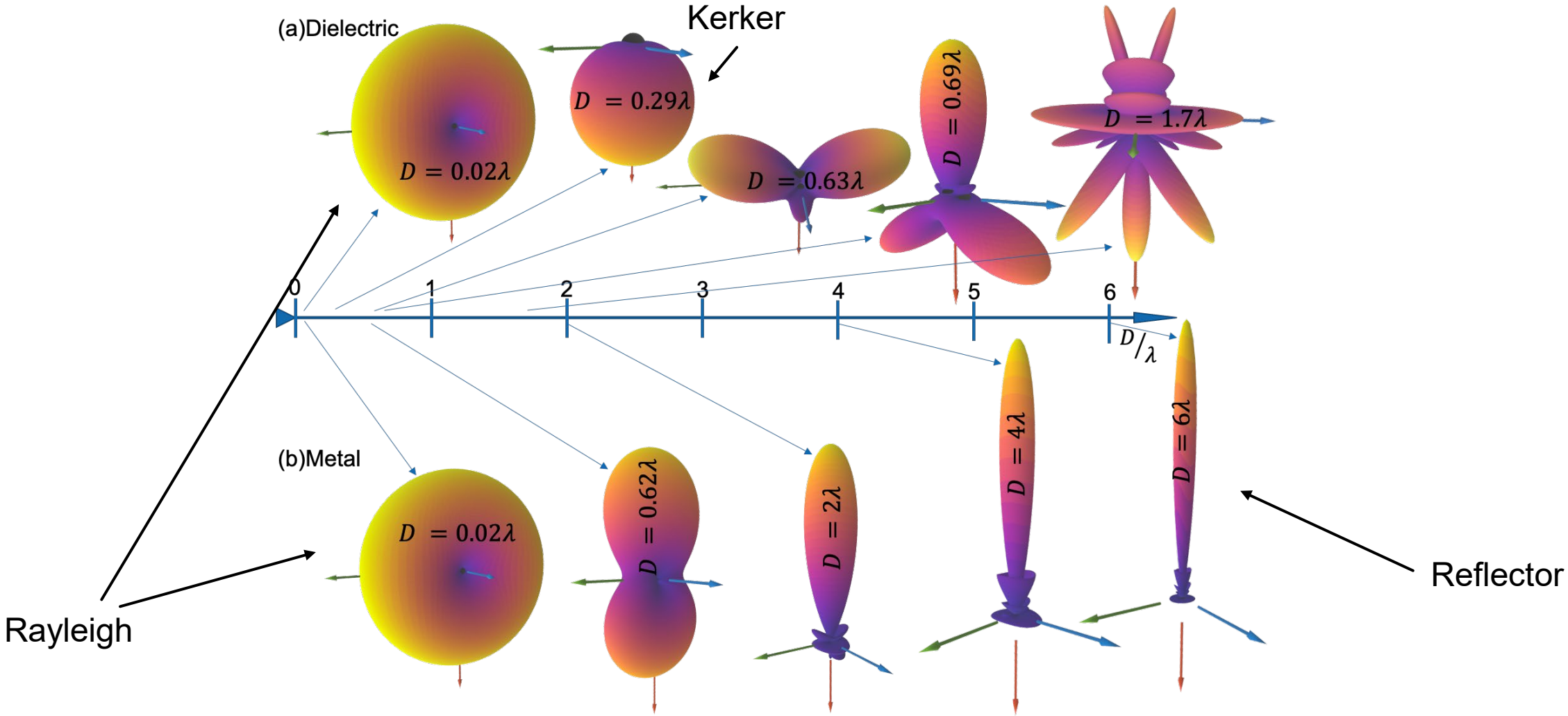
The vector fields in spherical coordinates

$$\vec{E} = \sum_{l,m} \left(p_{m,l} \vec{I}_{m,l} + q_{m,l} \vec{S}_{m,l} \right)$$



A. Dorodnyy, J. Smajic and J. Leuthold; „Mie Scattering for Photonic Devices"; Laser & Photonics Reviews, 2023

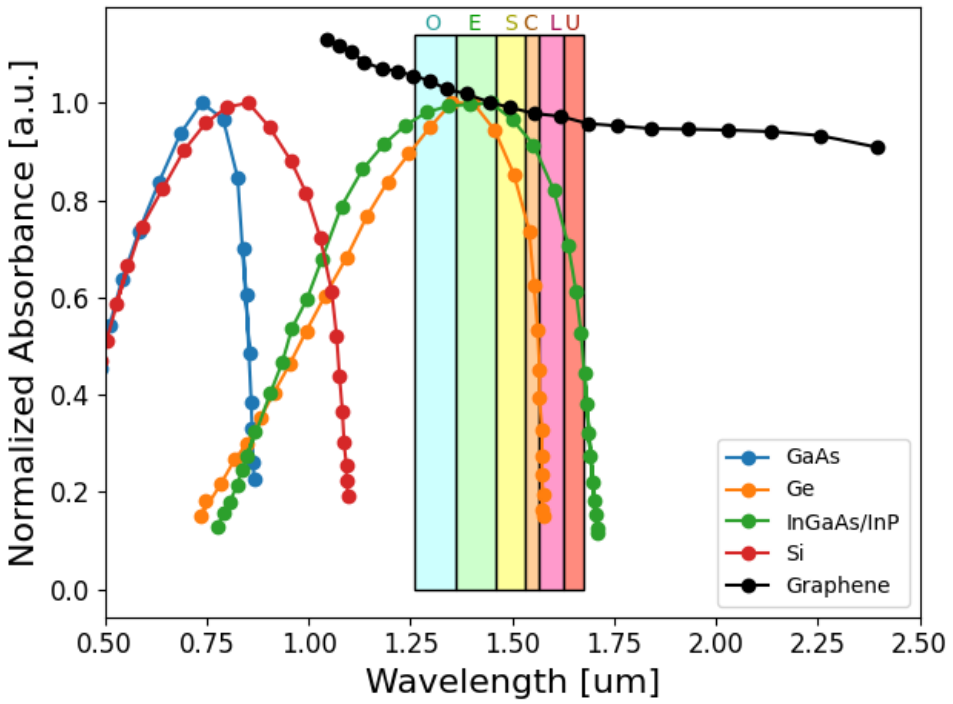
Mie Scattering – Farfield Dipole Solution



A. Dorodnyy*, J. Smajic and J. Leuthold; „Mie Scattering for Photonic Devices"; Laser & Photonics Reviews, 2023

Photodetection Absorber Materials

- Common photodetectors materials:
  - Limited optical bandwidth ($E_{ph} > E_g$ for absorption)
  - Limited electrical bandwidth (Low carrier mobility, large relative permittivity i.e. large RC response time)
  - …



Values for GaAs, Ge InGaAs/InP, Si taken from:
Saleh, Bahaa EA, and Malvin Carl Teich. *Fundamentals of photonics*. john Wiley & sons, 2019. p. 740

Values for Graphene taken from:
Mak, K. F. *et al.* Measurement of the Optical Conductivity of Graphene. *Phys. Rev. Lett.* **101**, 196405 (2008).

$Ga_xIn_{1-x}As$:

$$\mu_n \sim 8 * 10^3 \frac{cm^2}{Vs}$$

D.Chattopadhyay, S.K.Sutradhar, B.R.Nag, *J. Phys. C*, **14**, no.6, pp.891-908(1981).

Single Layer Graphene:

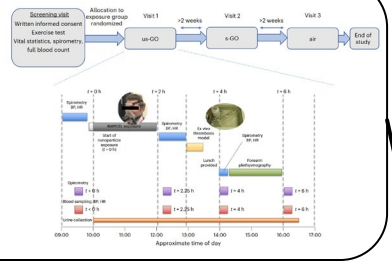
predicted: $\mu_n \sim 10^{15} \frac{cm^2}{Vs}$

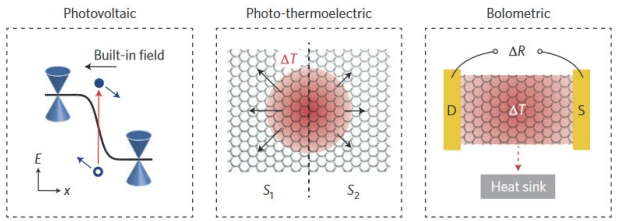
measured: $\mu_n \sim 8 * 10^4 \frac{cm^2}{Vs}$

Yamoah, M. A., Yang, W., Pop, E. & Goldhaber-Gordon, D. High-Velocity Saturation in Graphene Encapsulated by Hexagonal Boron Nitride. *ACS Nano* **11**, 9914–9919 (2017).

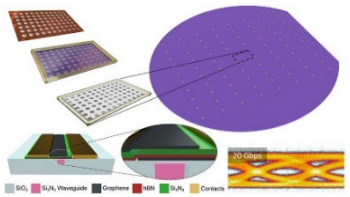
Graphene as an Absorber Solution

Andrews, J. P. M. *et al.* First-in-human controlled inhalation of thin graphene oxide nanosheets to study acute cardiorespiratory responses. *Nat. Nanotechnol.* **19**, 705–714 (2024).

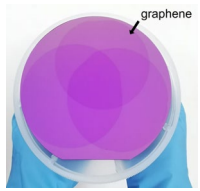




Koppens, F. H. L. *et al.* Photodetectors based on graphene, other two-dimensional materials and hybrid systems. *Nature Nanotechnology* **9**, 780–793 (2014).

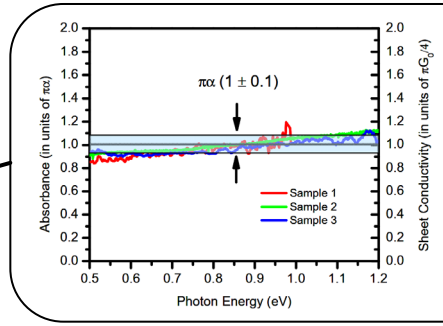


Giambra, M. A. *et al.* Wafer-Scale Integration of Graphene-Based Photonic Devices. *ACS Nano* **15**, 3171–3187 (2021).

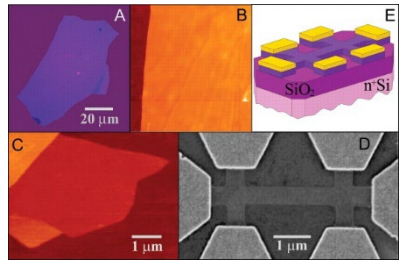


Yuan, G. *et al.* Stacking transfer of wafer-scale graphene-based van der Waals superlattices. *Nat Commun* **14**, 5457 (2023).

- Broadband absorption
- Non-toxic
- High carrier mobility
- **Graphene**
- Different Detection Mechanism Possible
- Platform independent solution
- Scalable

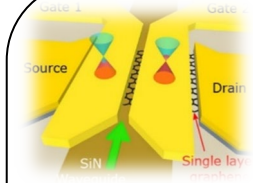


Mak, K. F. *et al.* Measurement of the Optical Conductivity of Graphene. *Phys. Rev. Lett.* **101**, 196405 (2008).



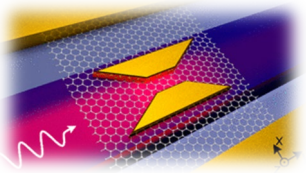
Novoselov, K. S. *et al.* Electric field in atomically thin carbon films. *Science* **306**, 666–669 (2004).

$\mu = 10^4 \frac{cm^2}{Vs}$ for single layer (limited by defects)



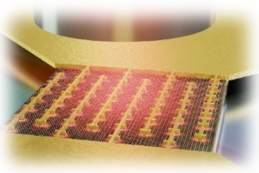
SiN WG

Muench, J. E. *et al.* Waveguide-Integrated, Plasmonic Enhanced Graphene Photodetectors. *Nano Lett.* **19**, 7632–7644 (2019).



Si WG

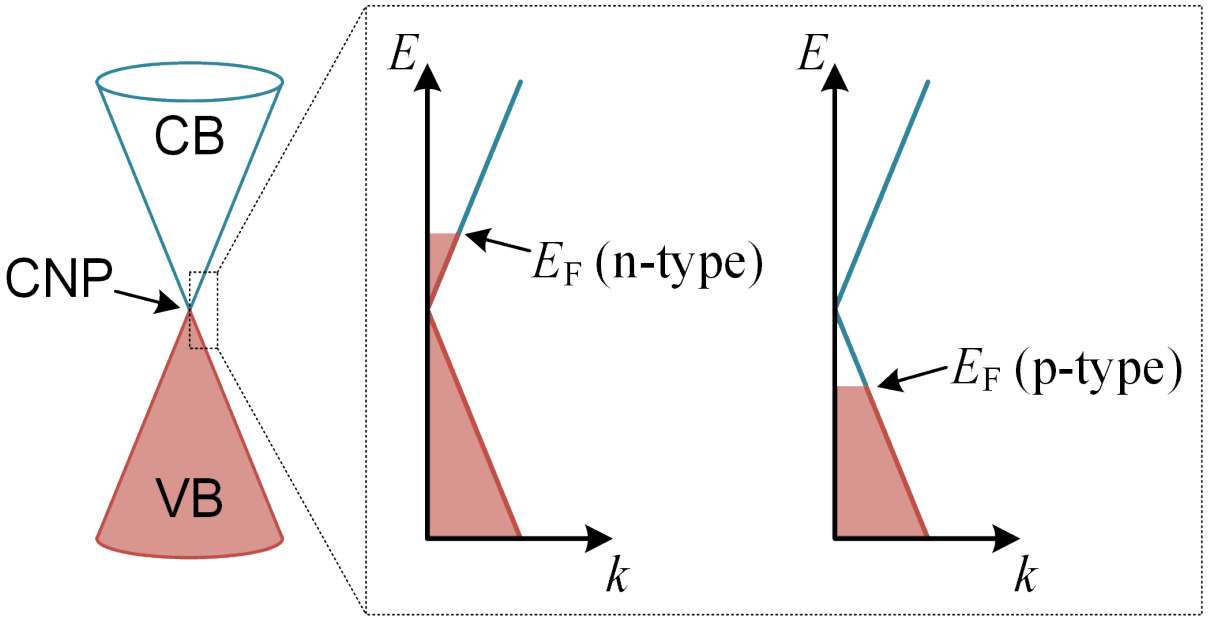
Ma, P. *et al.* Plasmonically Enhanced Graphene Photodetector Featuring 100 Gbit/s Data Reception, High Responsivity, and Compact Size. *ACS Photonics* **6**, 154–161 (2019).



SiO_2 Substrate

Koepfli, S. M. *et al.* Metamaterial graphene photodetector with bandwidth exceeding 500 gigahertz. *Science* **380**, 1169–1174 (2023).

Graphene: Bandstructure



The bandstructure

$E(k)=\pm\hbar v_F|k|$

Density of states:

$$\rho(E) = 4|E|/(2\pi(\hbar v_F)^2)$$

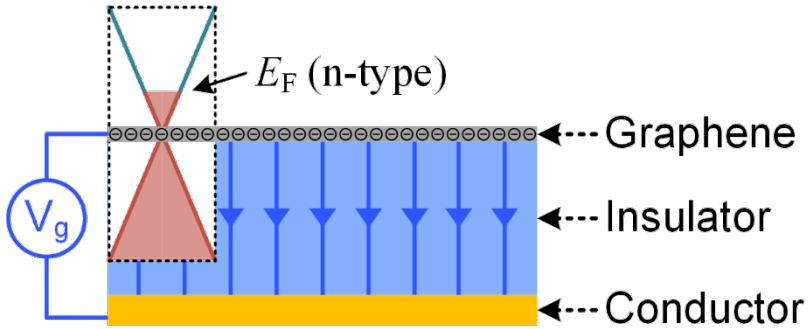
Carrier density

$$n = \int_0^\infty f(E)\rho(E)dE = \frac{4}{2\pi(\hbar v_F)^2}\int_0^\infty \frac{E}{1+e^{\left(\frac{E-E_F}{k_B T}\right)}}dE$$

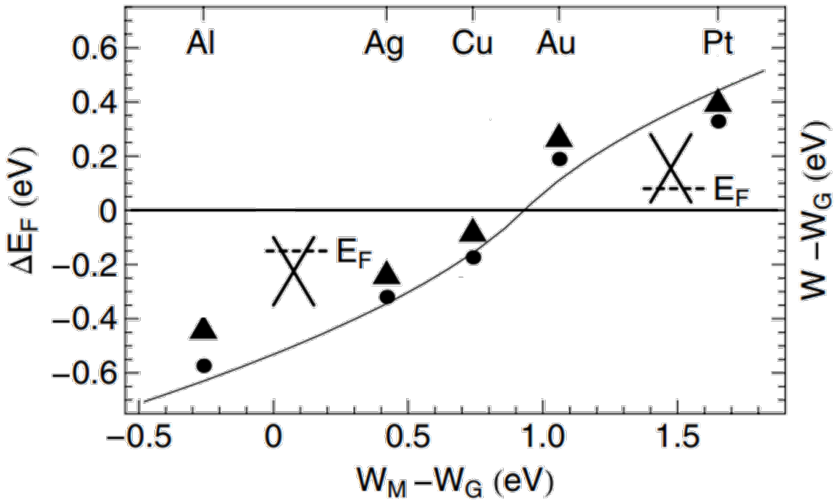
Graphene: Doping

2 doping techniques:

(a) Electrostatic field doping of graphene.



(b) Electrochemical doping of Graphene with a metal layer.



Shift of Fermienergy as a fct of applied voltage

$$E_F = \mathrm{sign}(V_g) \cdot \hbar v_F \sqrt{\frac{\varepsilon_0 \varepsilon_r \pi V_g}{q h_g}}$$

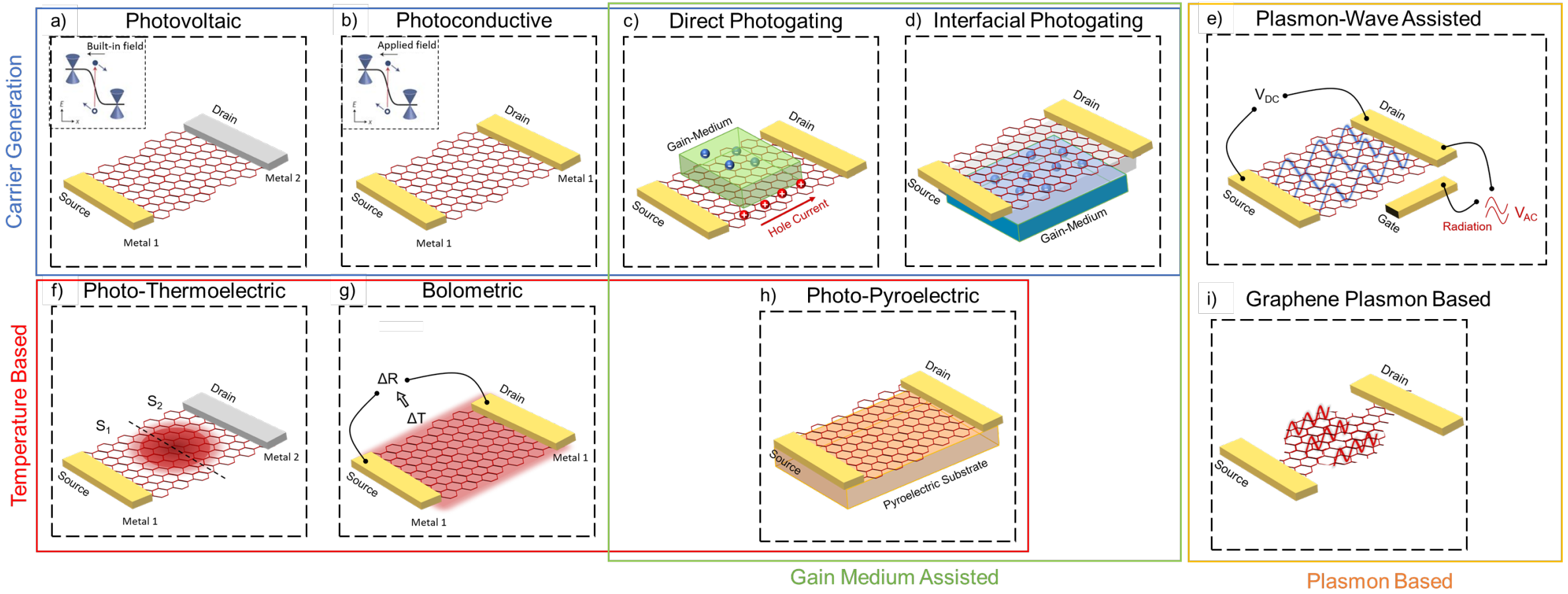
W: workfunction

Ref.: Y. Salamin, PhD Thesis, ETH Zurich, 2019

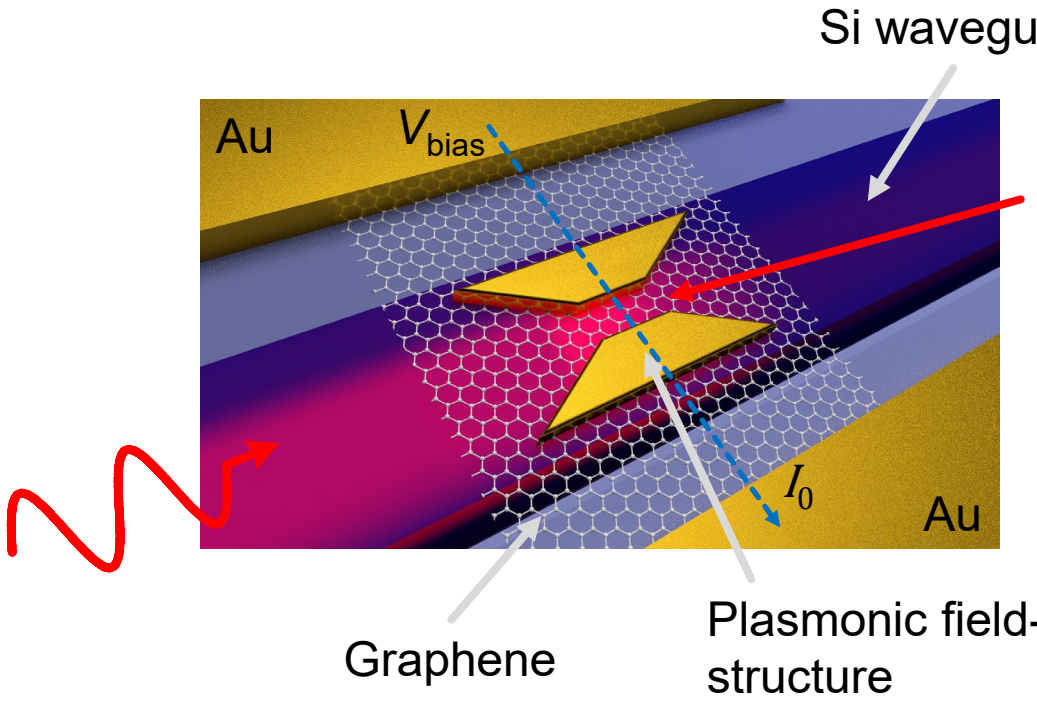
Ref.: G. Giovannetti, …, J. van den Brink, and P. J. Kelly, "Doping Graphene with Metal Contacts," *Physical Review Letters,* vol. 101, no. 2, 2008

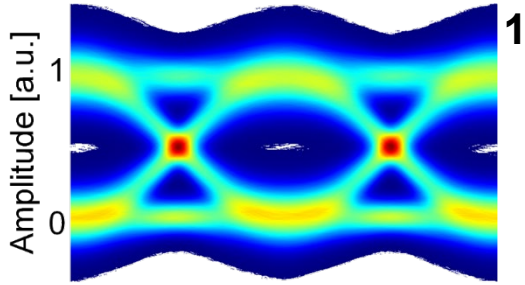
Graphene: Detection Mechanisms

- Direct detection mechanisms: PV, PC PTE, BOL – promise to be extremely fast
- Gain medium assisted: Direct photogating, interfacial photogating, photo-pyroelectric – high gain with responsivity of $10^8 A/W$
- Plasmon based detection: Plasmon-wave assisted, graphene plasmon based – Long wavelength operation FIR – THz

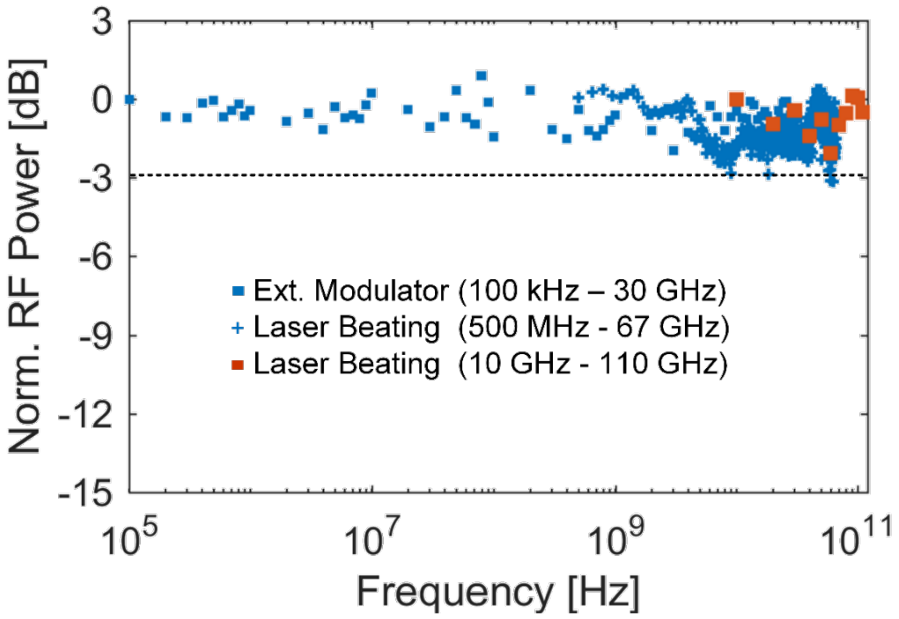


Plasmonic Enhanced Graphene Bolometric Detector



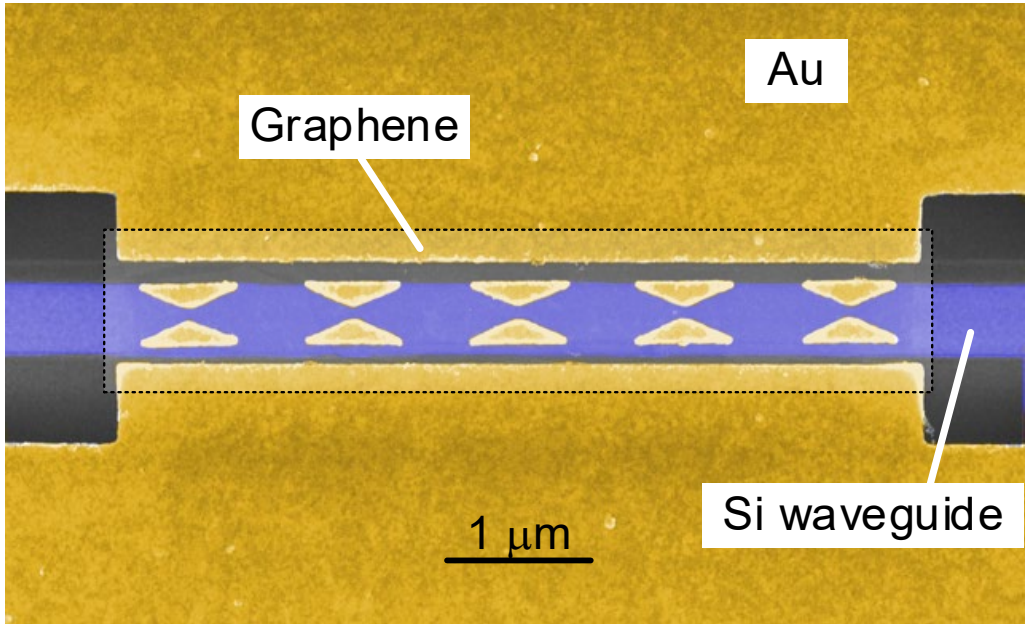


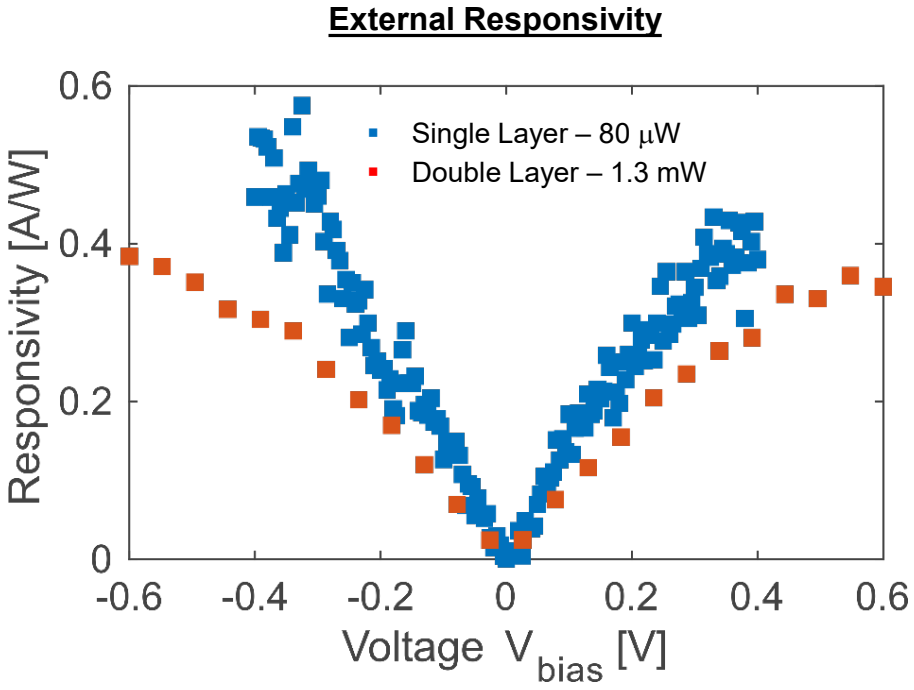
BER: 5.3 x 10^{-4}



*Ref.: Ma, Salamin, et al., ACS Photonics, **6**, 1 (2019)*

Device Structure and DC Performance



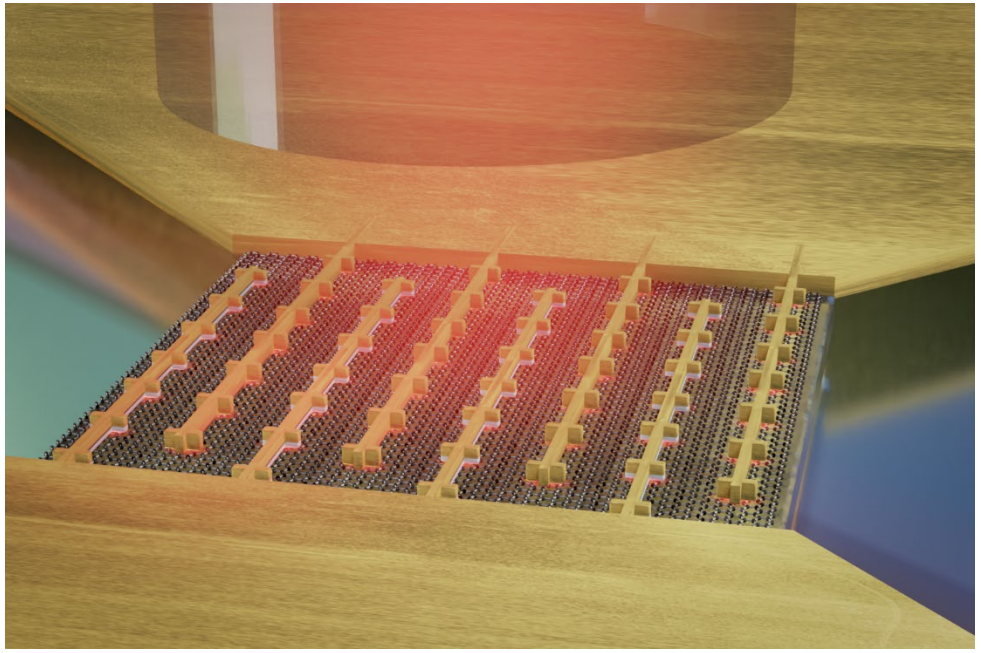


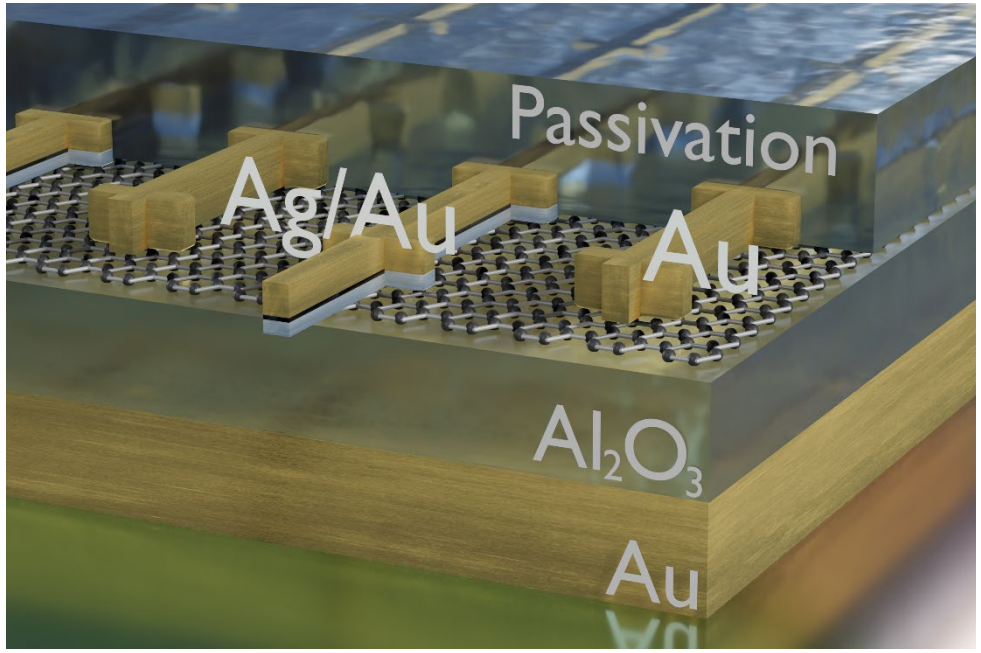
External Responsivity

~0.55 A/W for a **6 μm** long graphene detector @ 1550nm

Ma, Salamin, et al., *ACS Photonics*, **6**, 1 (2019)

Plasmonically (Metamaterial) Enhanced Graphene Photodetector



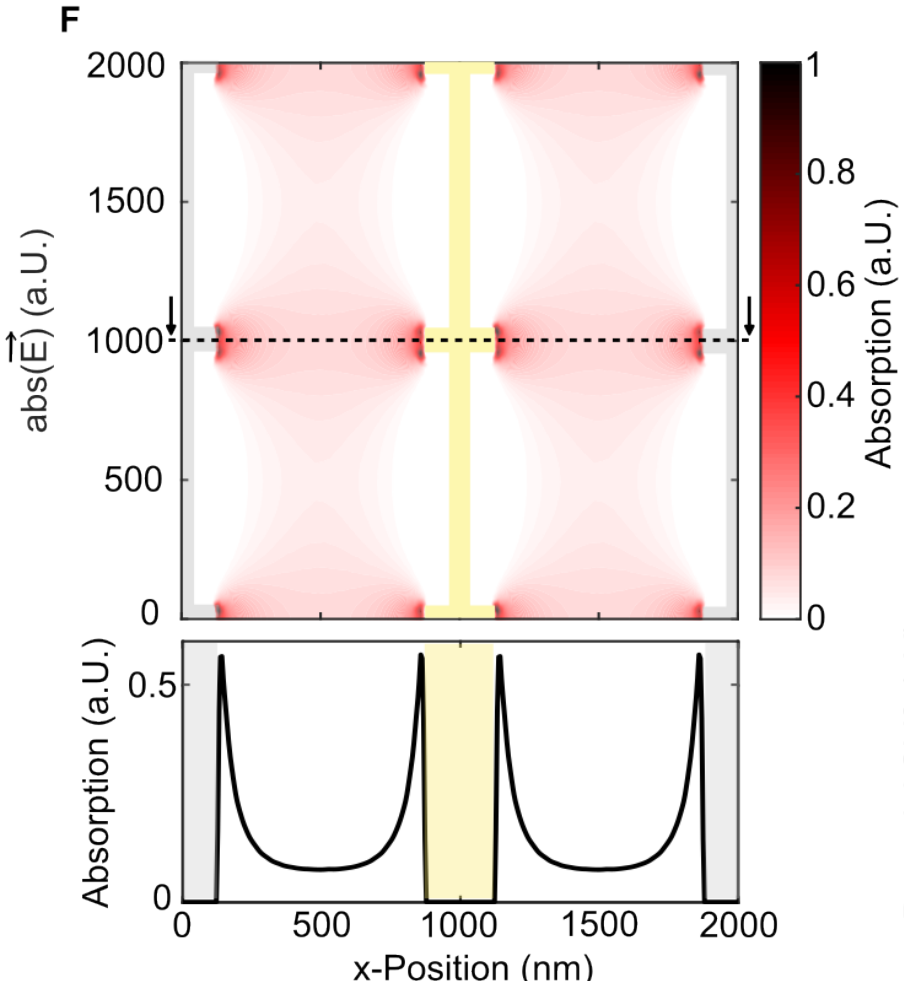


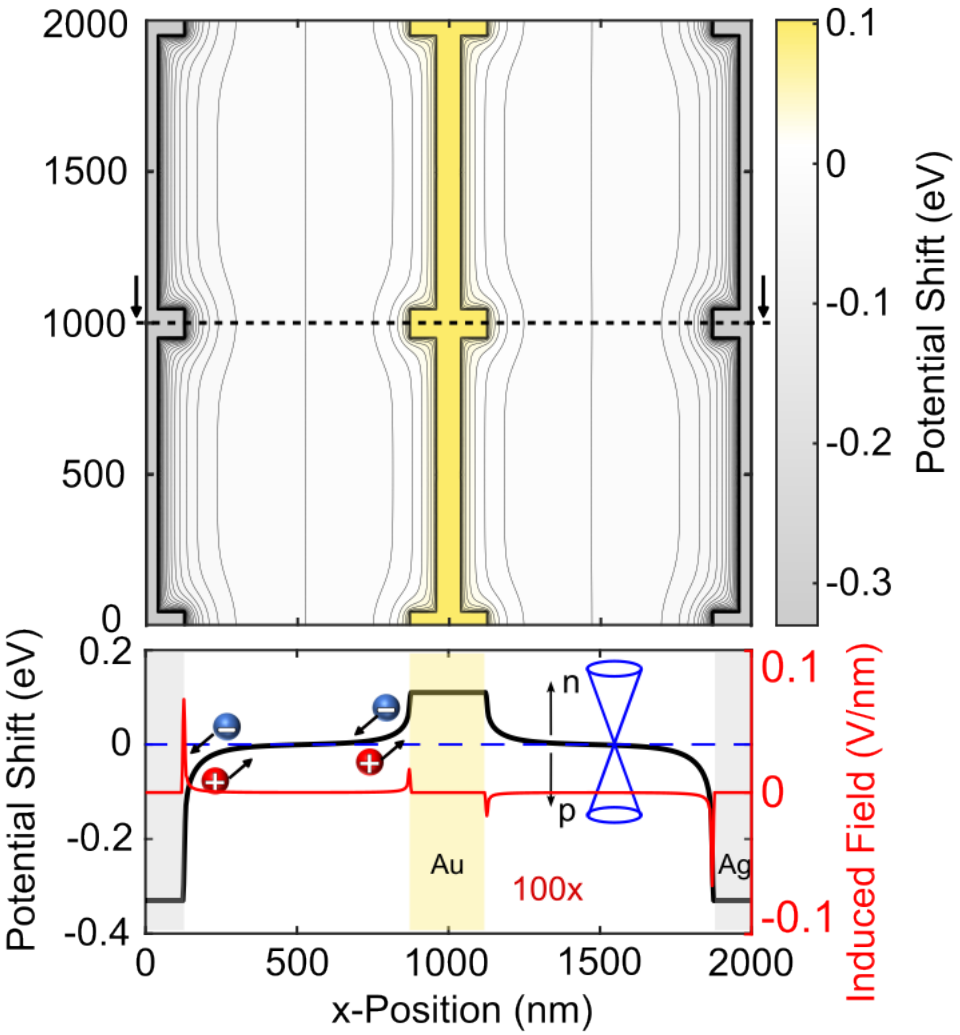
Main ideas of the stack:

- Graphene in metamaterial perfect absorber stack → enhances absorption in graphene
- Alternating contact metals → p-n doping the graphene channel
- Dipole resonators are combined with contact lines → short carrier extraction pathways

S. M. Koepfli *et al.*, "*Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz,*" *Science, 2023,*

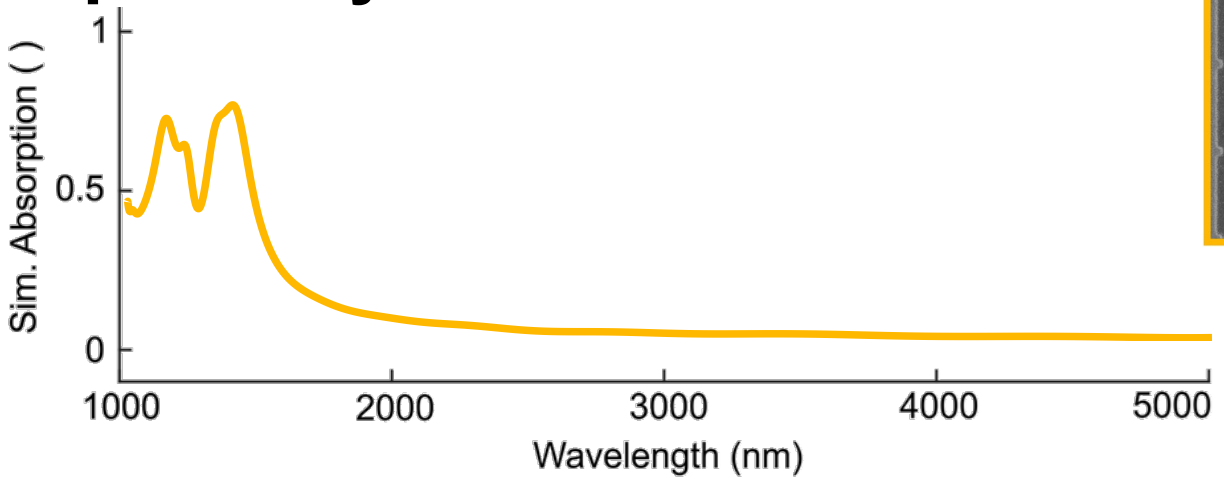
Plasmonically Enhance Graphene Detector: Physics

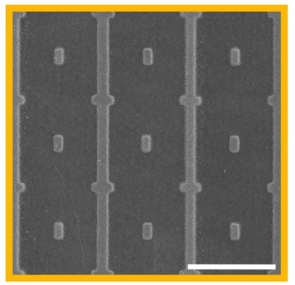




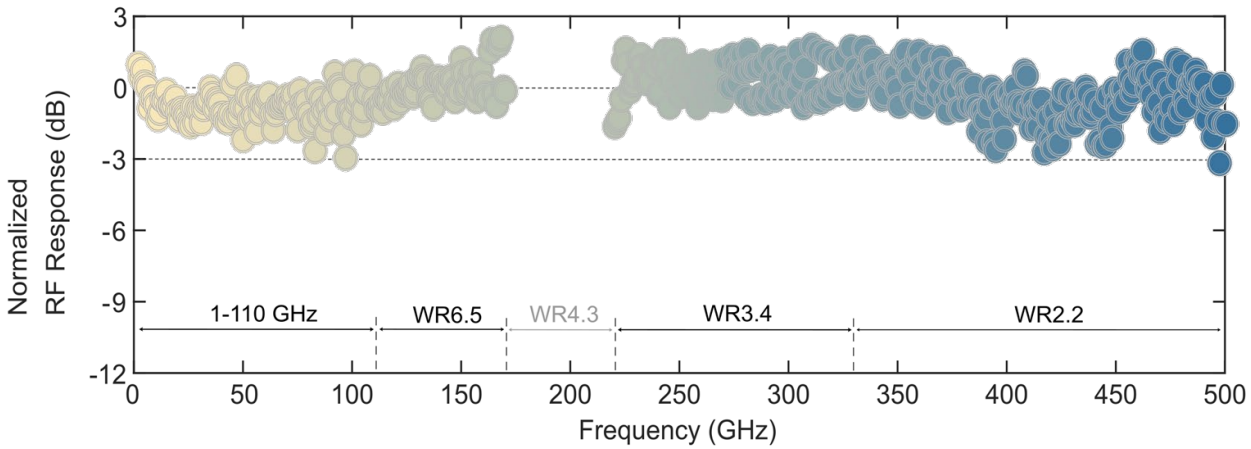
S. M. Koepfli *et al.*, "*Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz,*" *Science, 2023,*

Spectrally Broadband





Highest Speed Operation

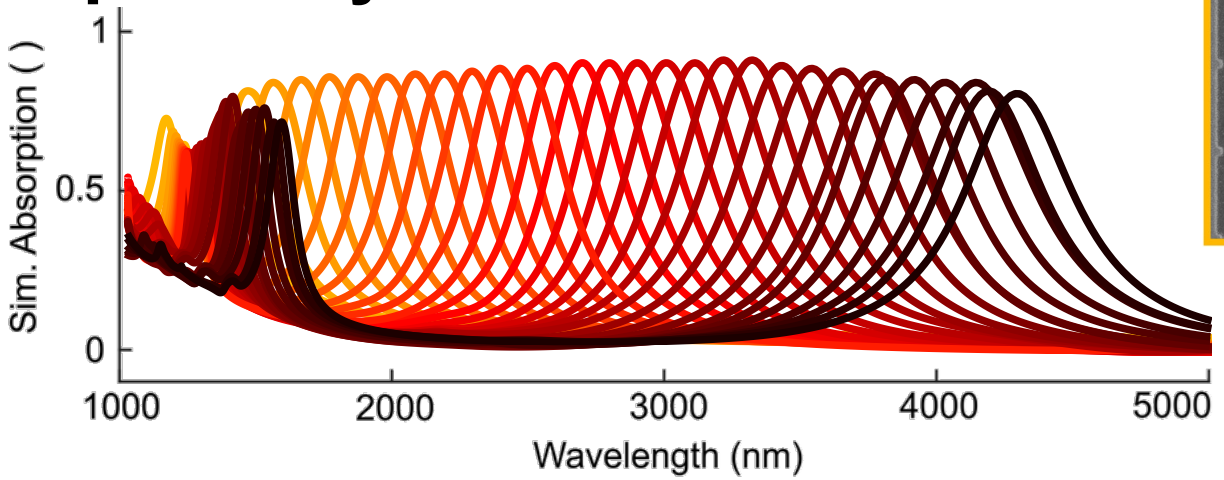


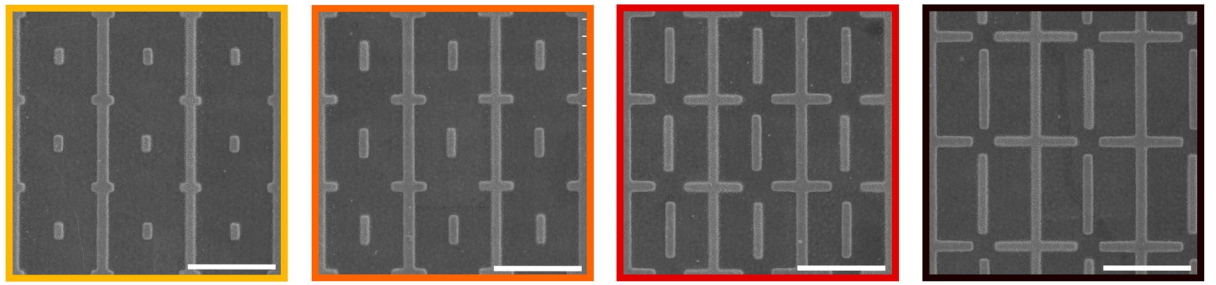
- Flat frequency response from 2 to 500 GHz

→ World's fastest photodetector

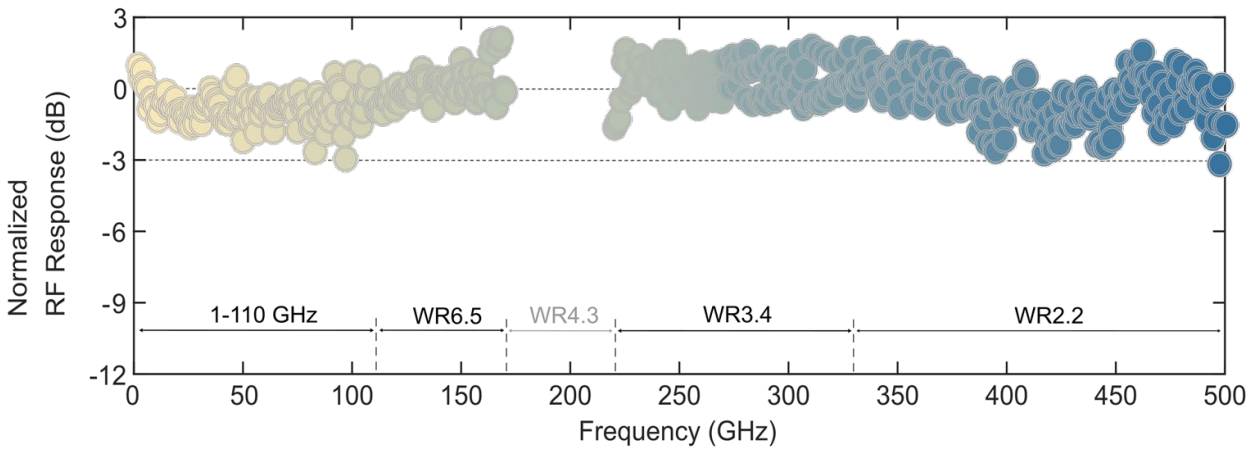
S. M. Koepfli *et al.*, "*Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz,*" *Science, 2023,*

Spectrally Broadband





- Spectral adaptability across the infrared spectrum



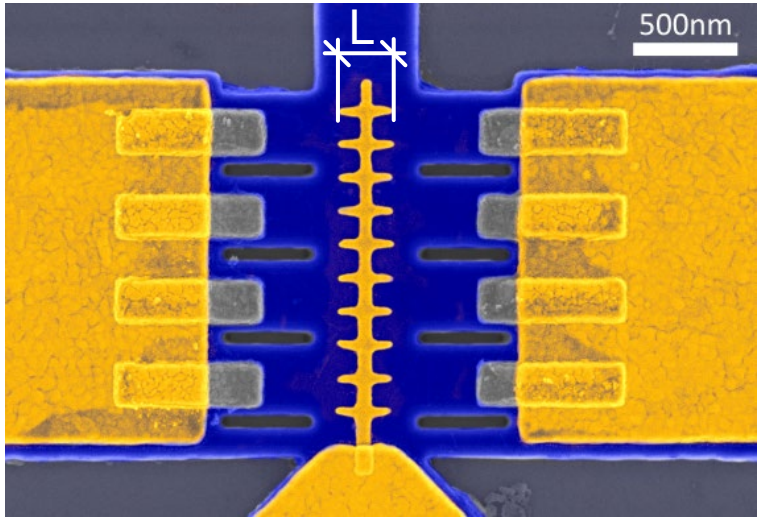
- Flat frequency response from 2 to 500 GHz

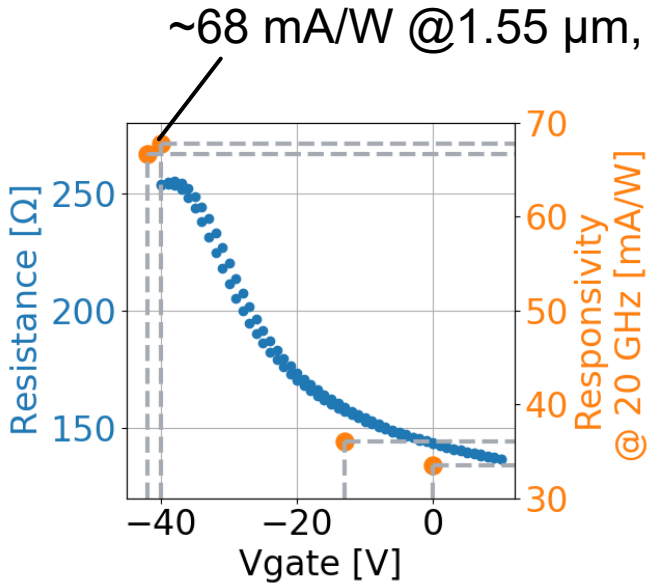
→ World's fastest photodetector

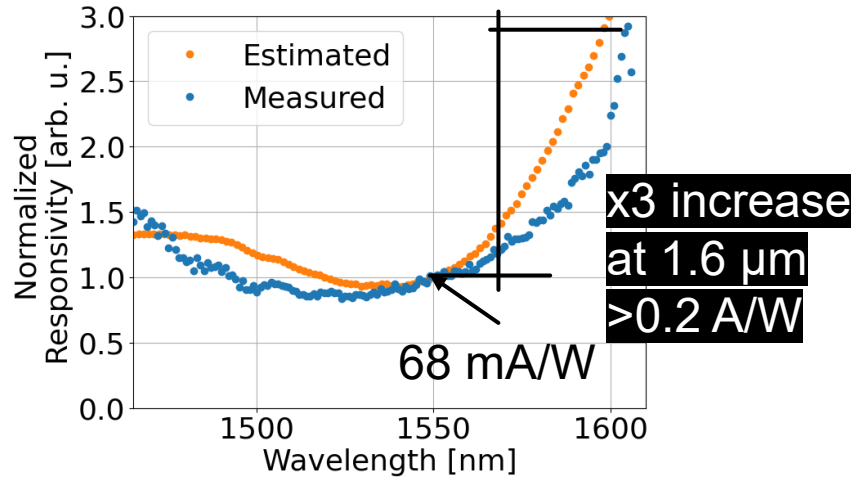
S. M. Koepfli *et al.*, "*Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz,*" *Science, 2023,*

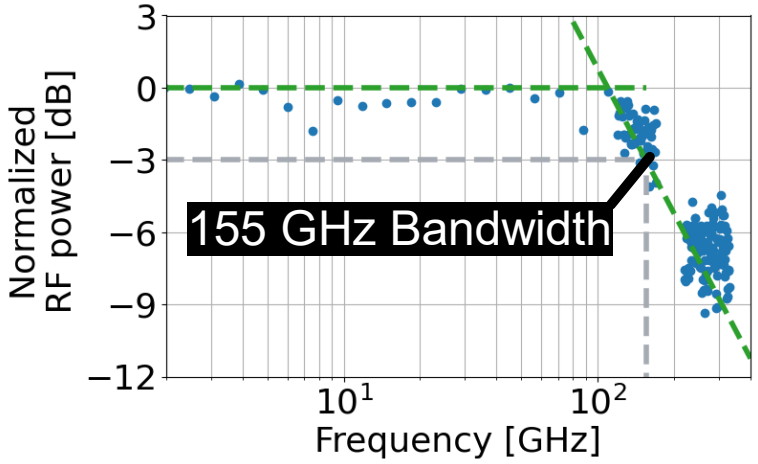
Thank you

Characterization of Waveguide Integrated Graphene Detector









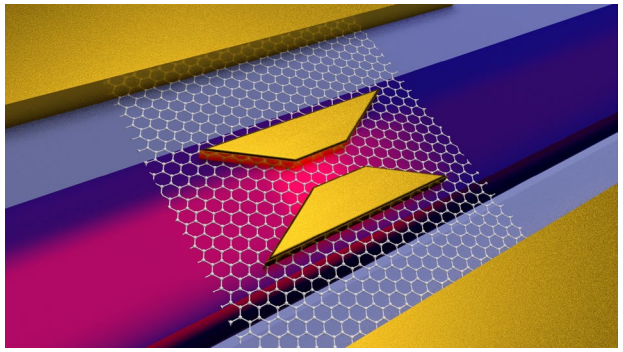
- Highest responsivity at Dirac Point ~68 mA/W, I_{dark}~1.2 mA
- >0.2 A/W at 1.6 µm
- Measured bandwidth of 155 GHz

Ref.: D. Rieben, et. al., "Towards 200 GBaud Line Rates with Waveguide-Integrated Plasmonic Graphene Photodetectors," in *Optical Fiber Communication Conference (OFC) 2025(Optica Publishing Group, San Francisco, California, 2025),*

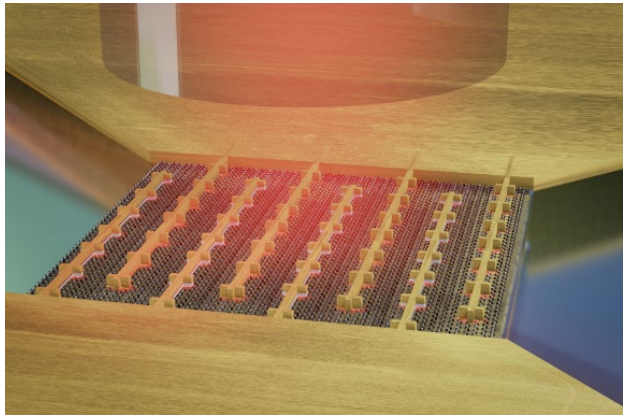
Summary

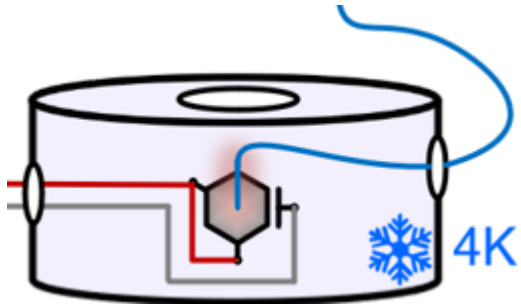
Graphene Plasmonics – a solution for fast, sensitive, compact detection at any temperature!

100 GHz bolometric

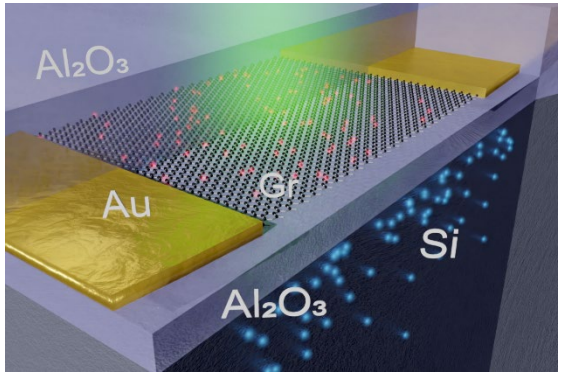


500 GHz PV detection





At 4 K



Senstive by photogain effect