ETH zürich

# Plasmonic Metamaterials – New Techniques for Sensing

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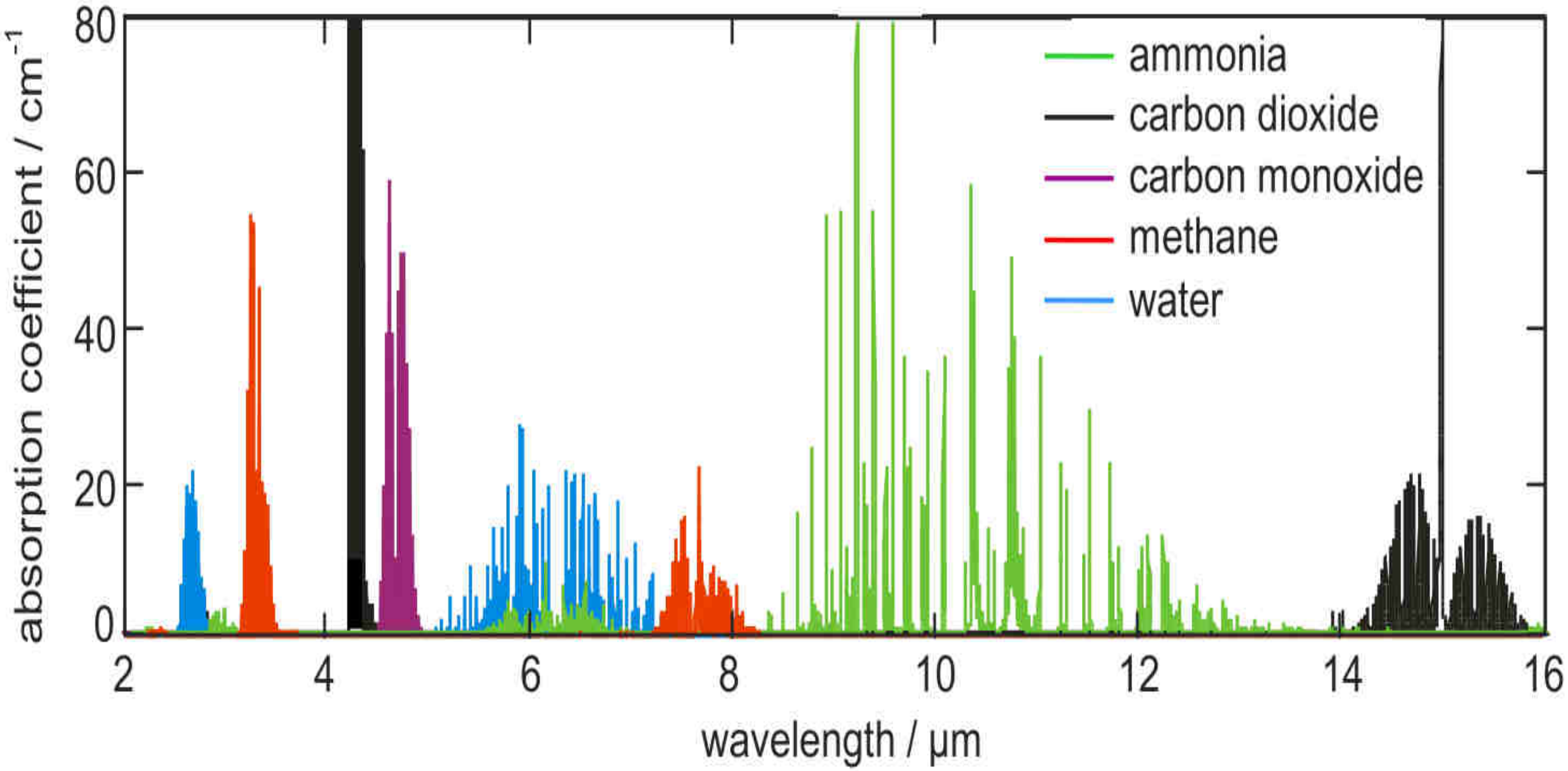
[1] ETH Zurich, Switzerland,

# Content

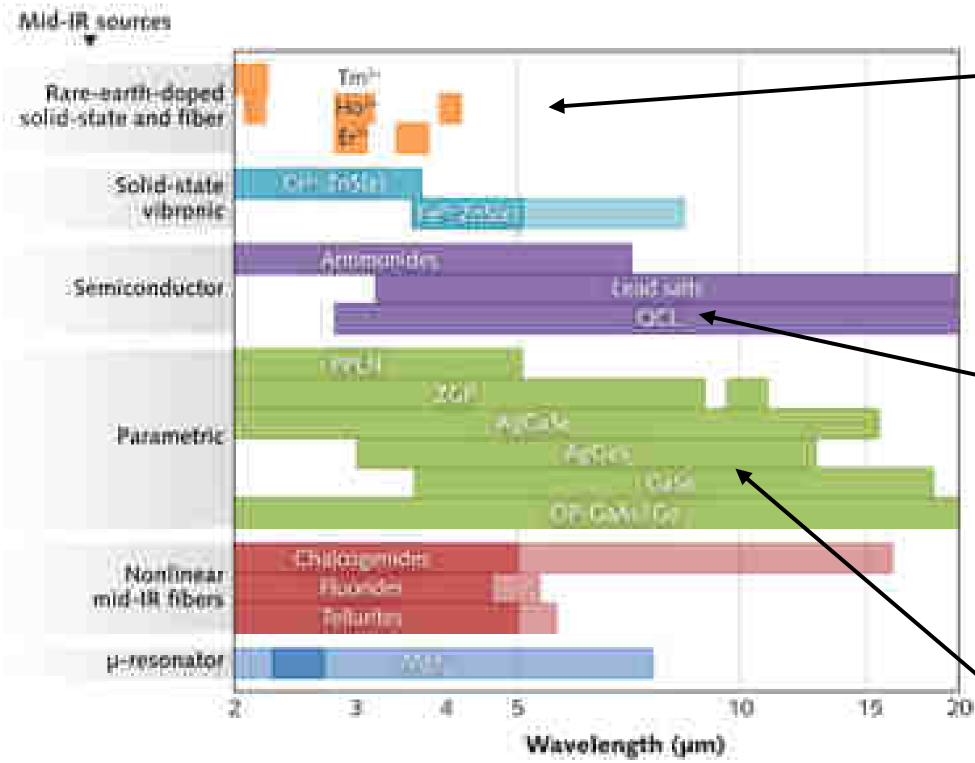
- A Metamaterial Mid-IR Emitter
- Surface Plasmon Polaritons (SPPs)
- A SPP interferometric detector

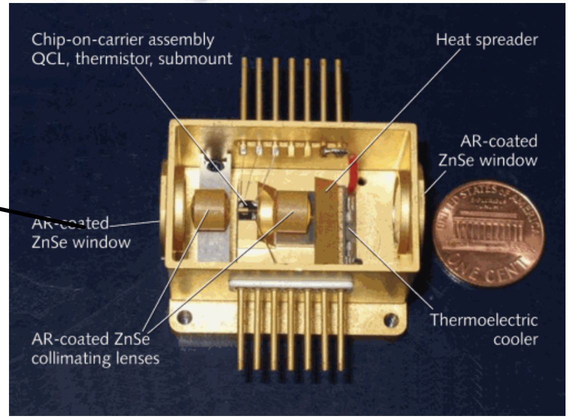
# Gas Detection at Mid-IR




http://lightsensetechnology.com/core-technology/

# Mid-IR Sources



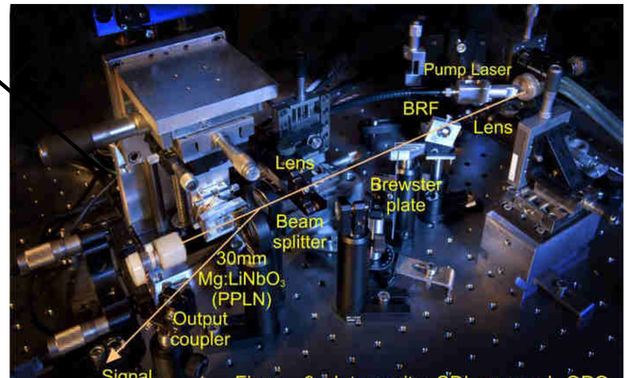
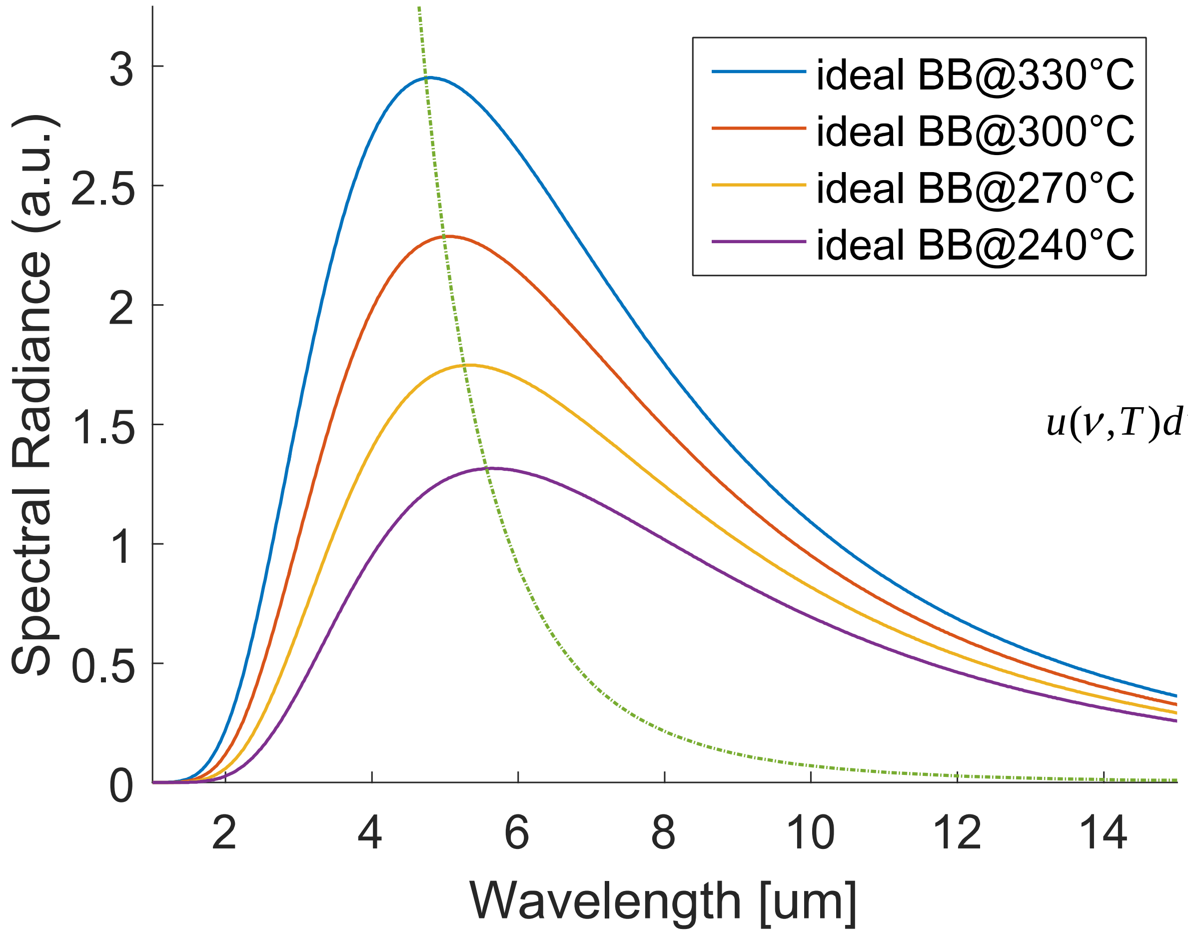




Figure 3: Intracavity SDL-pumped OPO emitting from λ=2.8-3.6 and 1.5-1.7 μm [9].

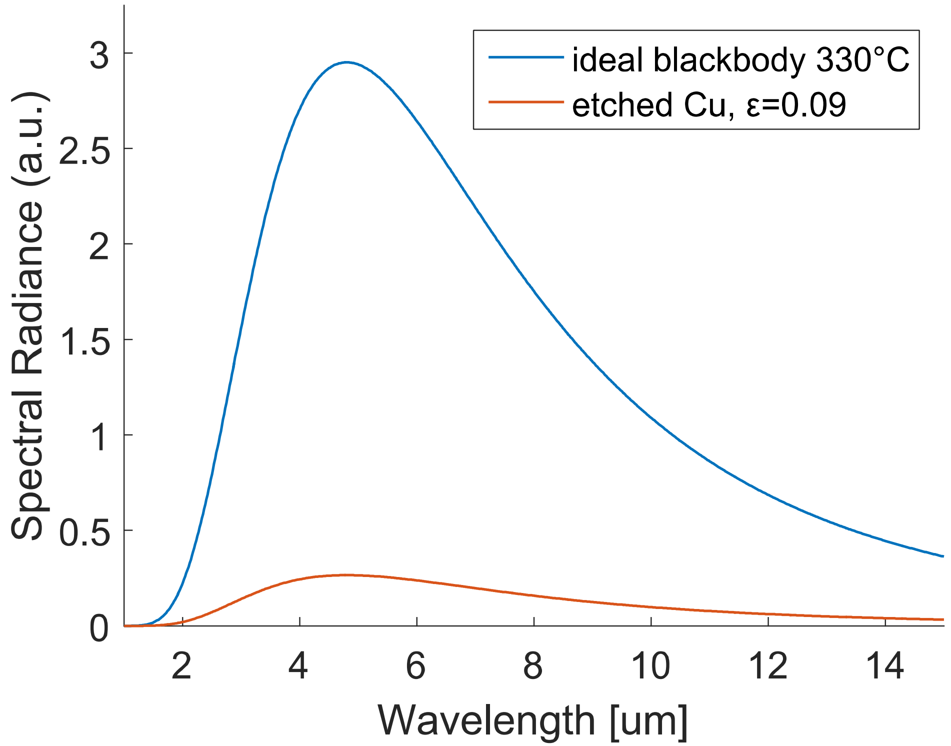
# The Planck Law




$$u(\nu,T)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/k_BT}-1}d\nu$$

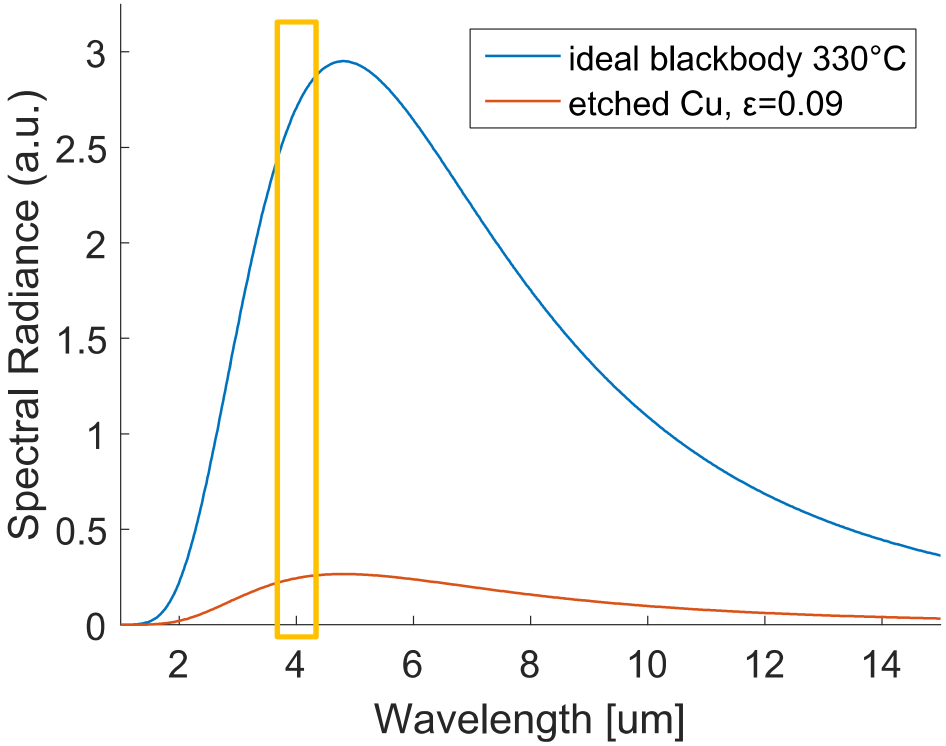
# The Planck Law

Issue 1: Emission normally low



# The Planck Law

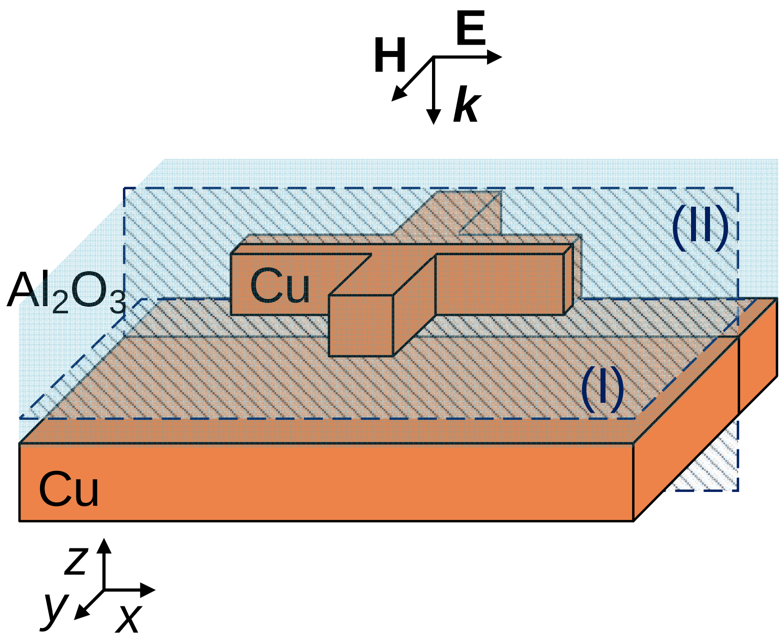
Issue 2: Broadband Emission

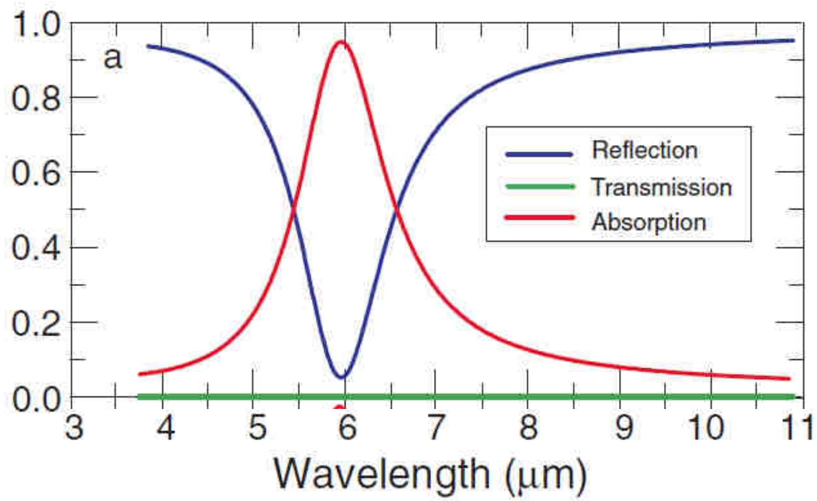



Only fraction of power around absorption peak of gas is needed.

Remaining spectral components will degrade performance of detector due to saturation.

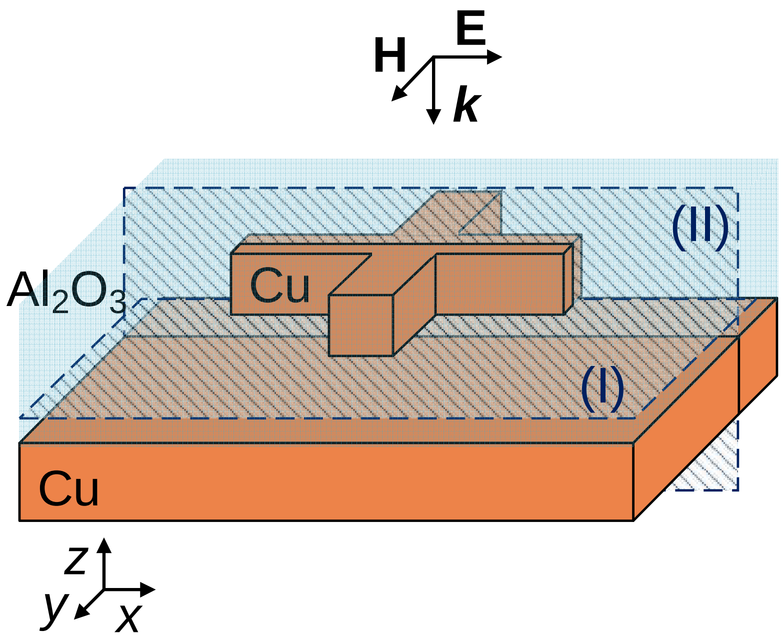
# A Metamaterial Perfect Absorber




X. Liu, T. Starr, A. F. Starr, and W. J. Padilla, "Infrared Spatial and Frequency Selective Metamaterial with Near-Unity Absorbance," Physical Review Letters **104, 207403 (2010).**

# A Metamaterial Perfect Emitter?



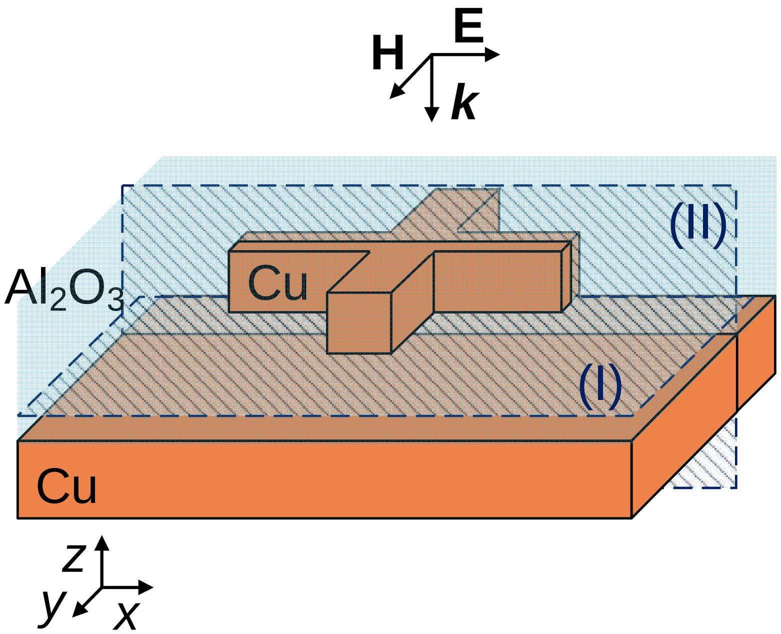

**Kirchhoff's law:**

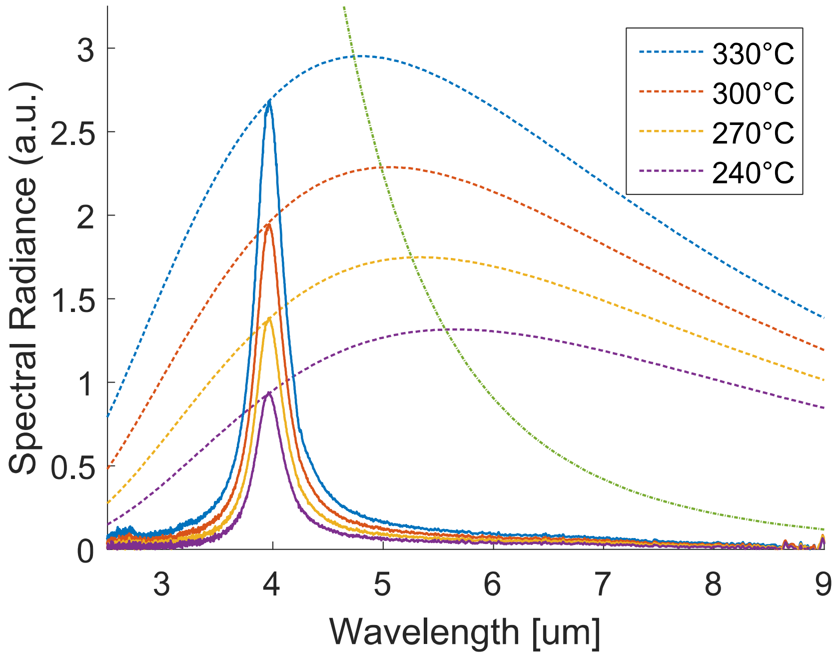
Emissivity=Absorptivity

$$e_\lambda = \alpha_\lambda$$

A. Lochbaum et al.; Submitted to OSA Sensors Meeting

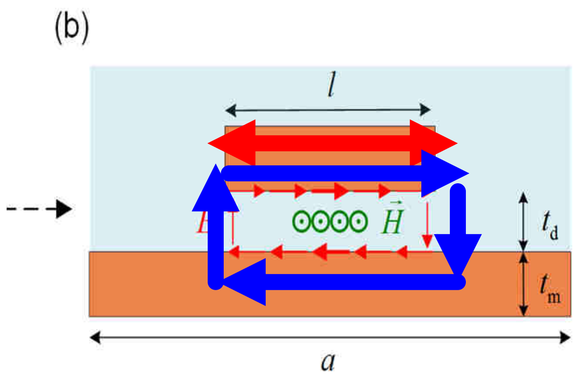
# A Metamaterial Perfect Emitter

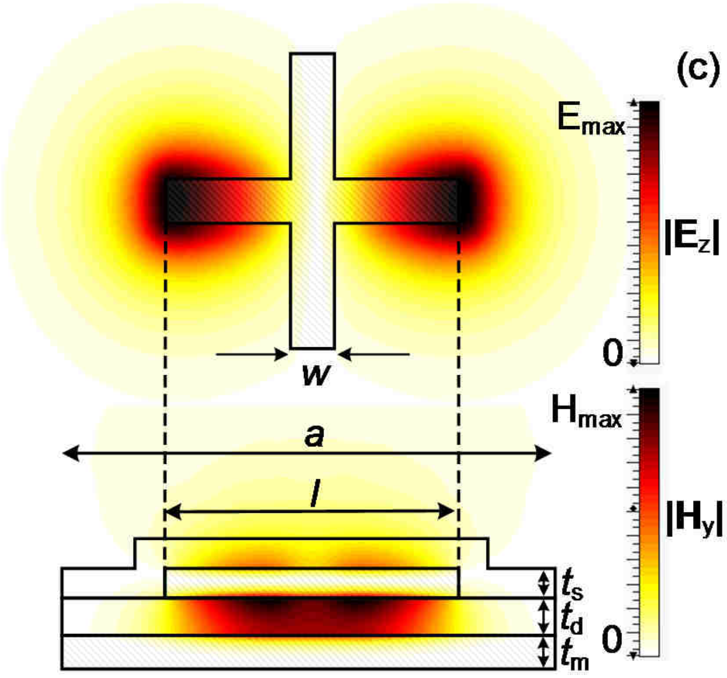



A. Lochbaum et al.; Submitted to OSA Sensors Meeting

# A Metamaterial Perfect Emitter- The Physics

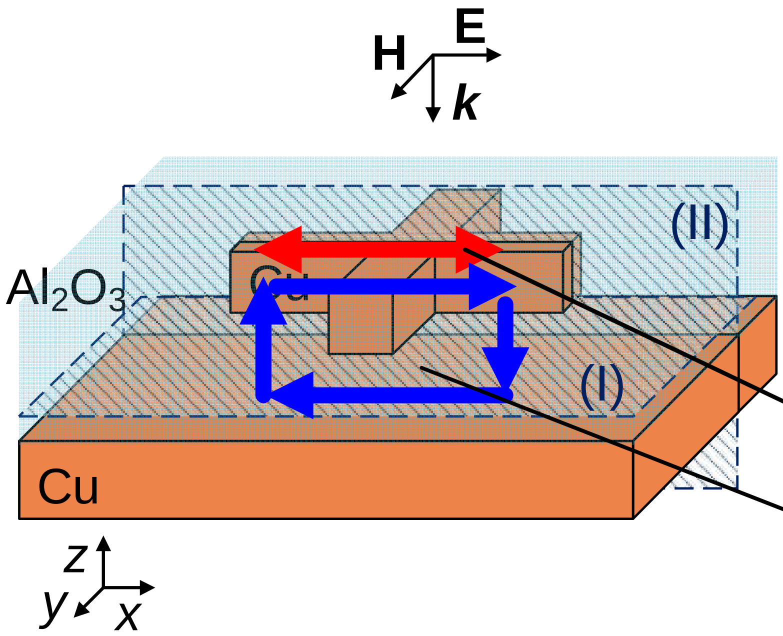



i) EM thermal fluctuation induces a current in top electrode
ii) Current in top electrode induces H-field in spacer
iii) H-field induces current in opposite direction in bottom metal

A. Lochbaum et al.; Submitted to OSA Sensors Meeting

# A Metamaterial Perfect Emitter – El. Field Theory

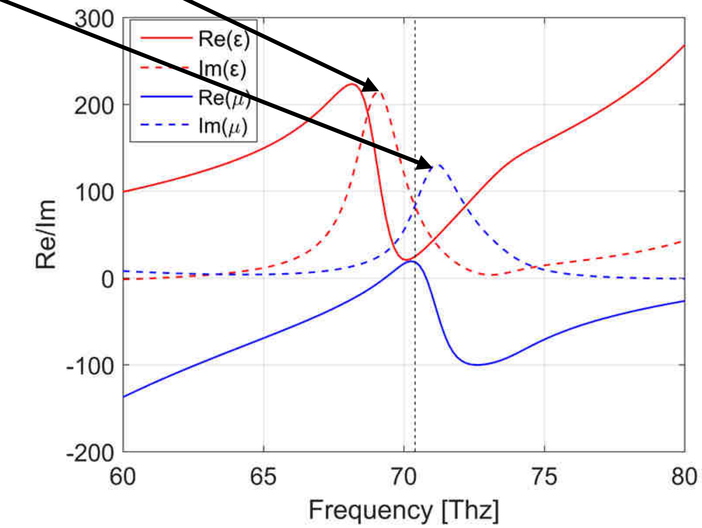



With Kirchoff:
If $A$=1 then $E$=1

If $T$+$R$+$A$=1 ➔ $A$=1

Find geometry such that R=0

Transmisson=0 (reflector)

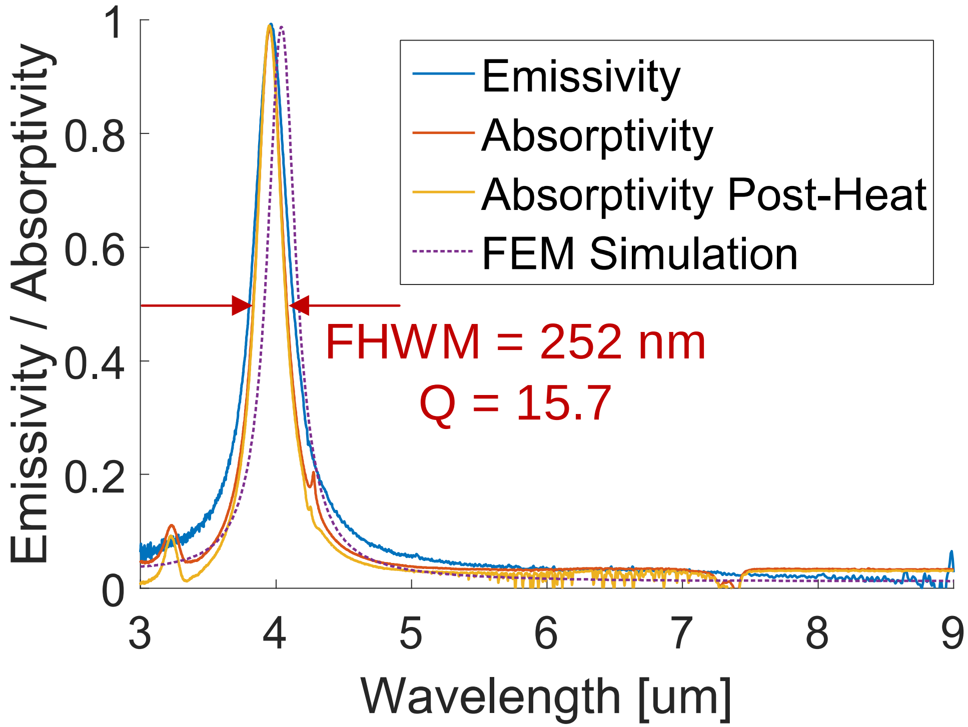



i) $R$=0 if impedance $Z = \sqrt{\frac{\mu_r(\omega)}{\varepsilon_r(\omega)}} = 1$ matched to air.

ii) By tweaking dimensions, one can tweak $\mu$ and $\varepsilon$ independently

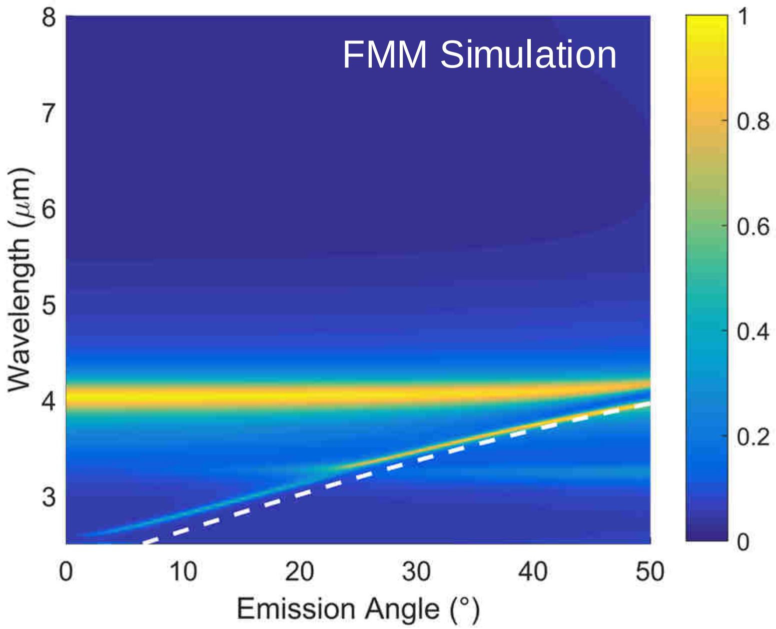
iii) Tune to spot where $\mu_r(\omega)$=$\varepsilon_r(\omega)$

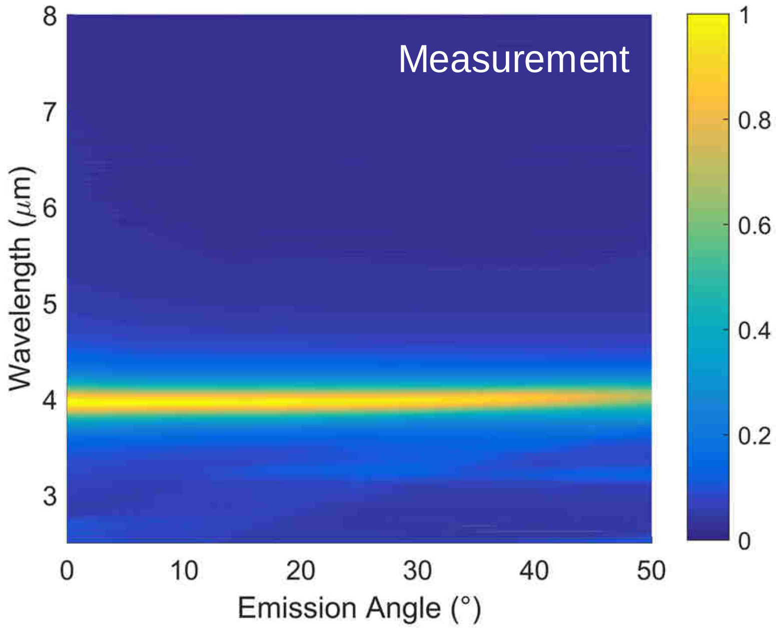
# A Metamaterial Perfect Emitter - Characterization



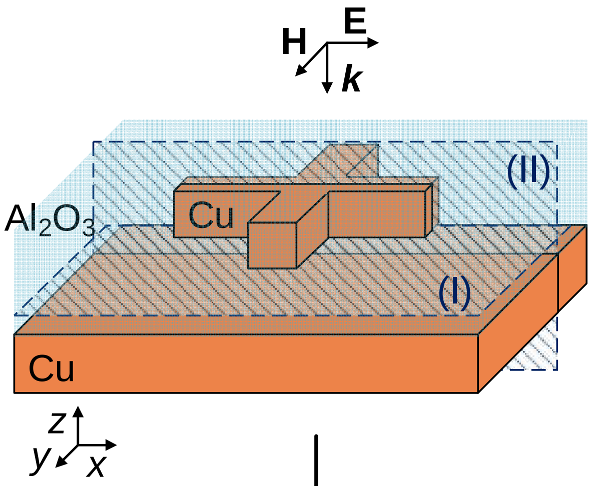

A. Lochbaum et al.; Submitted to OSA Sensors Meeting

# A Metamaterial Perfect Emitter – Angular Depend.

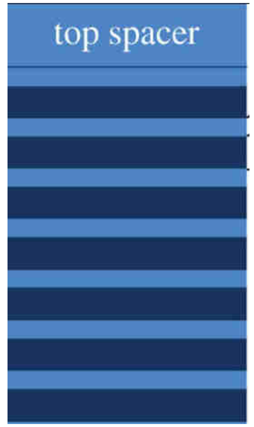


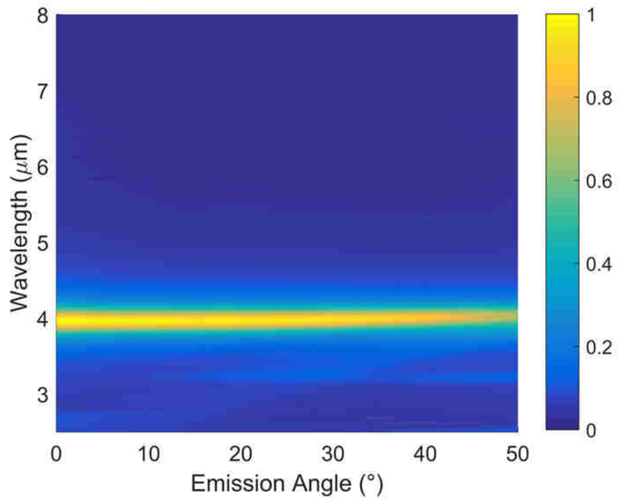



# Perfect Emitter with a Frequency Selective Filter

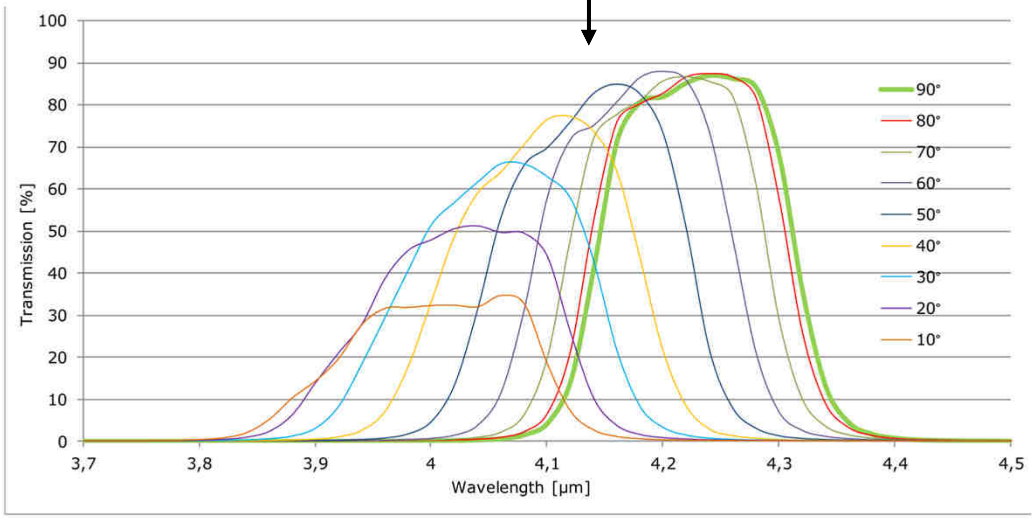



Plasmonic filter versus
Bragg Grating filter



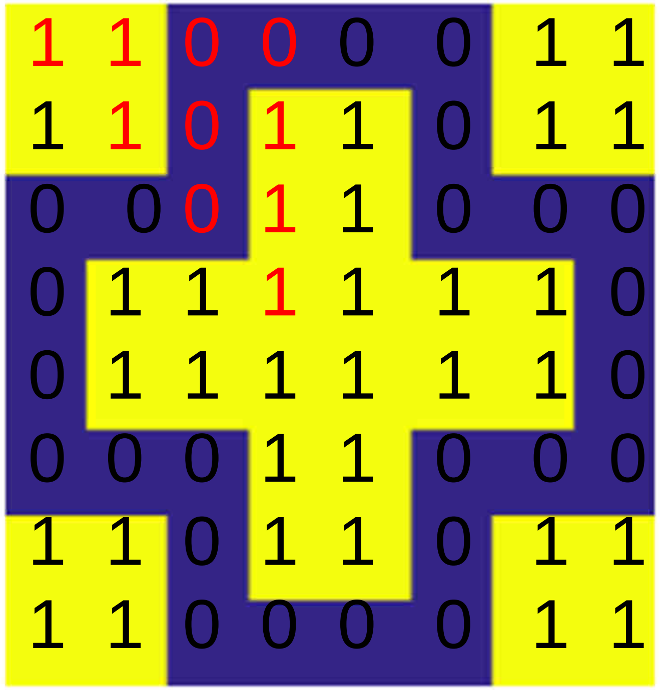



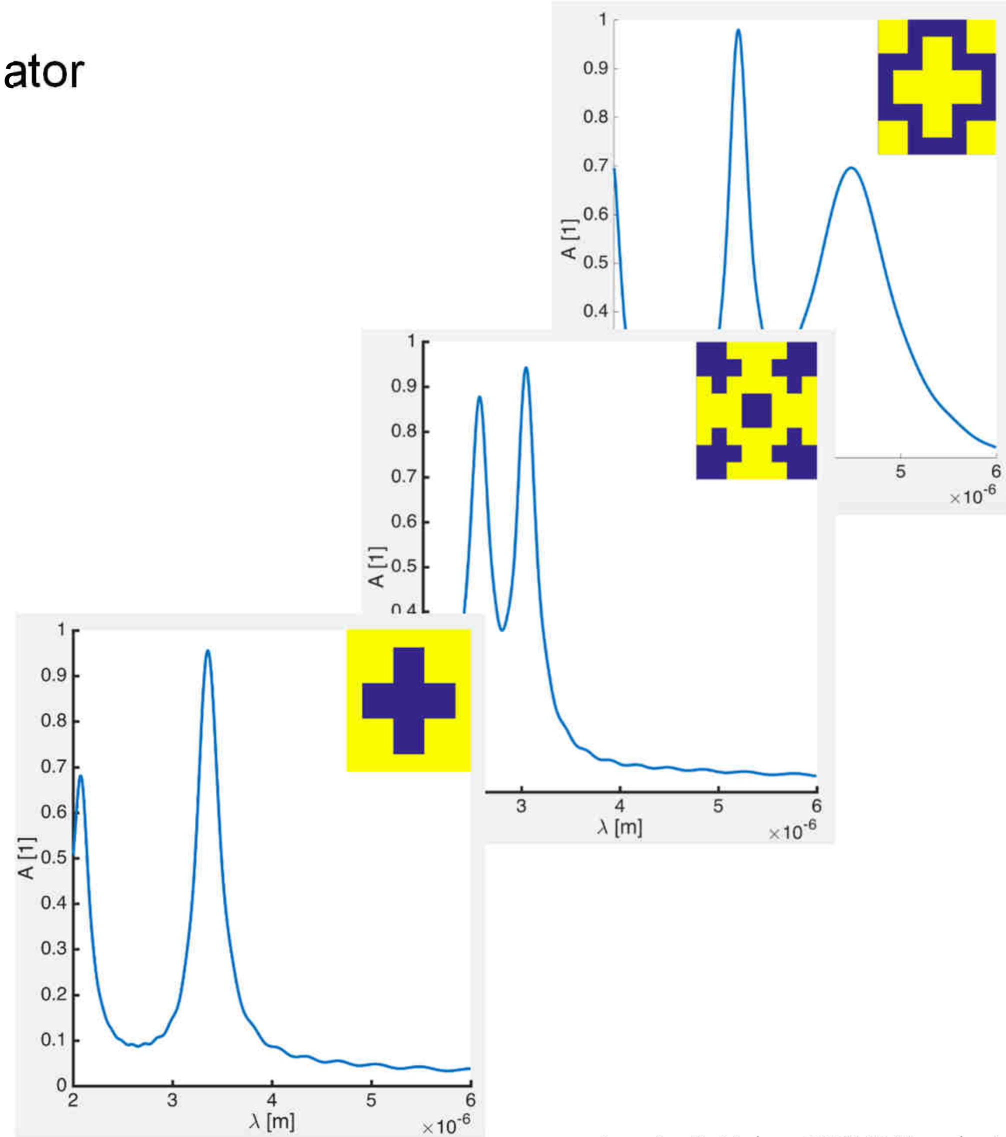

A Bragg Grating filter has an angular dependence



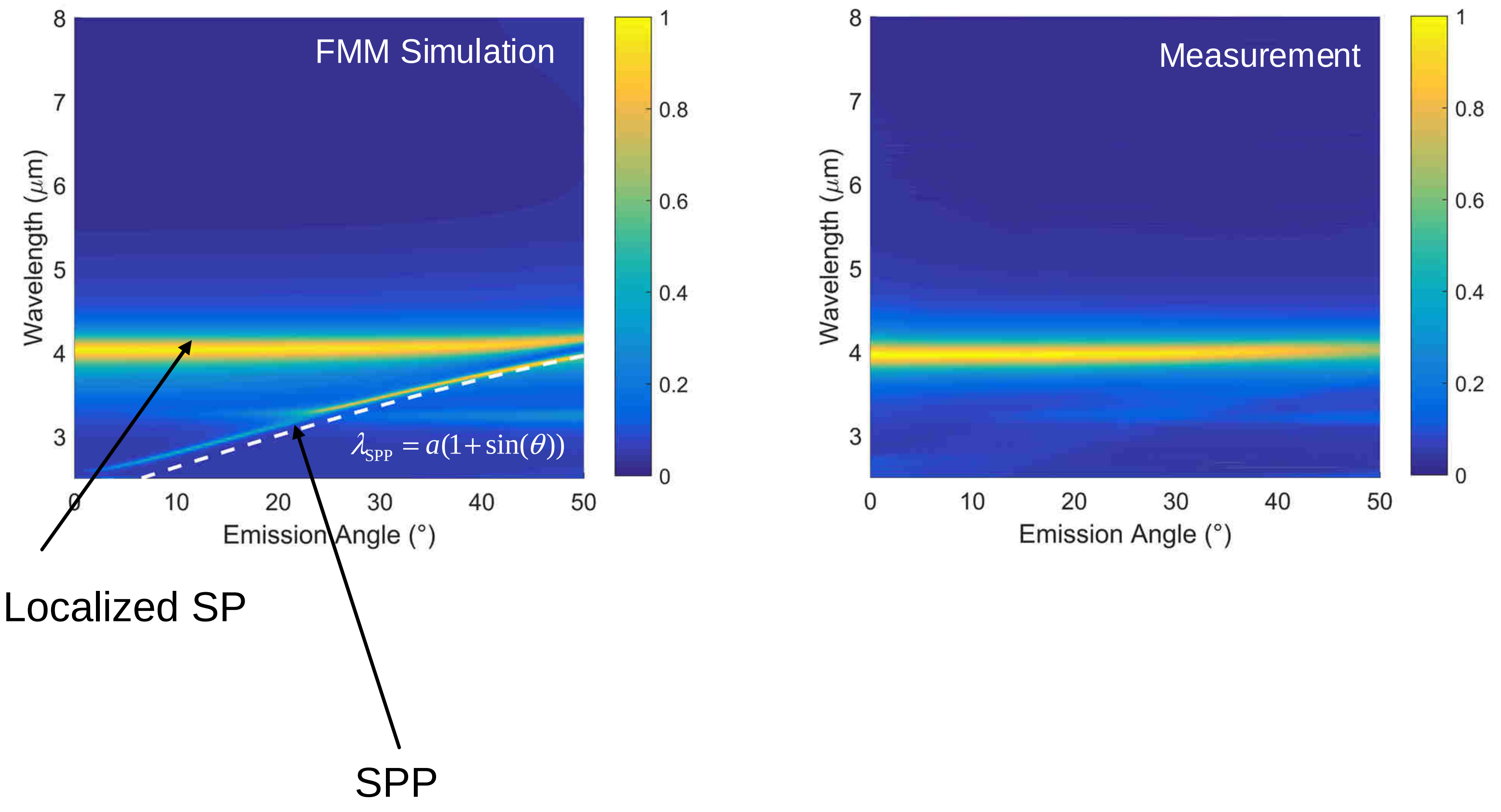
# Are we Sure to Have the Perfect Emitter?

Global Optimization of Top Resonator



# A Metamaterial Perfect Emitter – Angular Depend.



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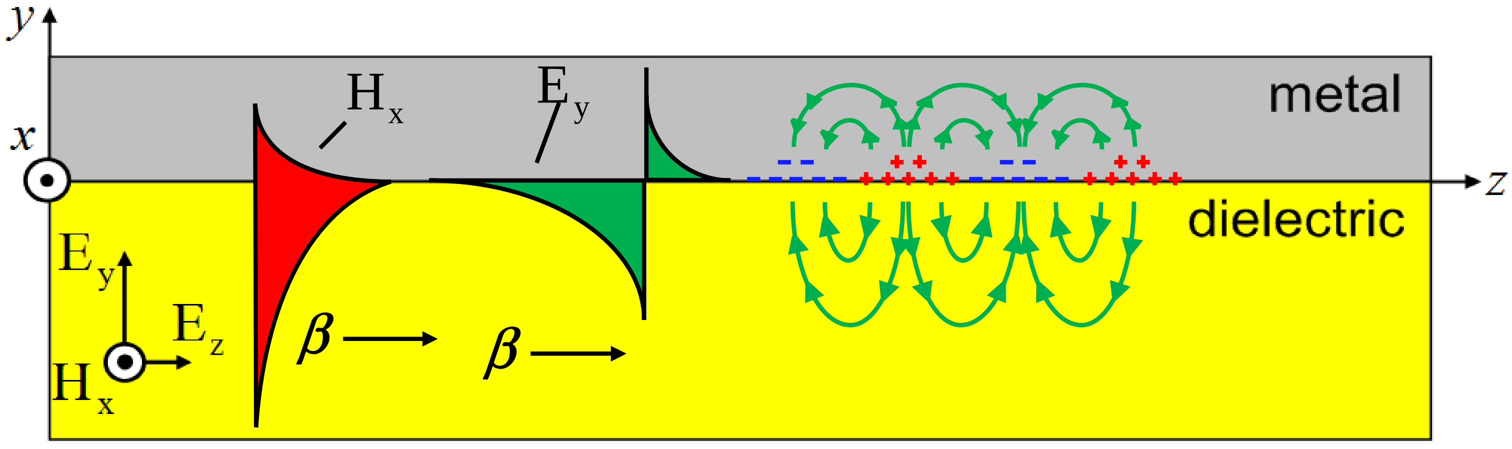
# Surface Plasmon Polariton (SPP)

**Plasmon:** Coherent electron gas oscillations

**Polariton:** If coupled to light

**SPP:** Coherent electron gas oscillation coupled to light at surface.




**Derivation**: Wave Equation

$$\frac{d^2 H_x(y)}{dy^2} + \left[k_0^2 \varepsilon(y) - \beta^2\right] H_x(y) = 0,$$

Boundary Conditions

$$H_{x,m} = H_{x,d} \qquad \varepsilon_m E_{y,m} = \varepsilon_d E_{y,d}$$

➔ Dispersion Relations

$$\beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}$$

# Surface Plasmon Polariton

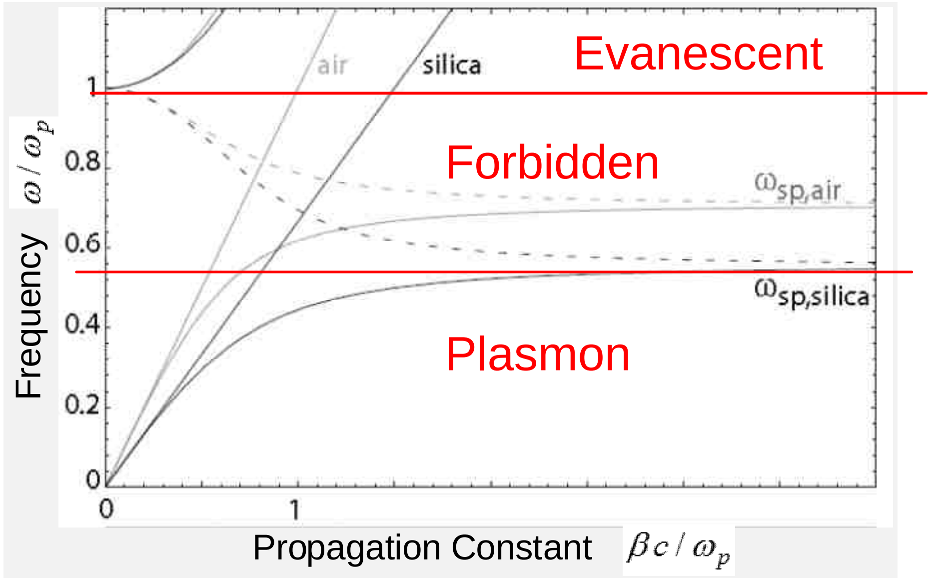
- Derive Mode and Dispersion

➔ Dispersion relations for ideal conductor

→ $\varepsilon_1'' = \mathrm{Im}[\varepsilon_1] = 0$

$$\beta = k_0 \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} = \frac{\omega}{c_0} \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

$$\varepsilon_1(\omega) \cong 1 - \frac{\omega_p^2}{\omega^2}$$




➔ Dispersion relations for lossy conductor:

→ $\varepsilon_1 = \varepsilon_1' - \mathrm{j}\varepsilon_1''$

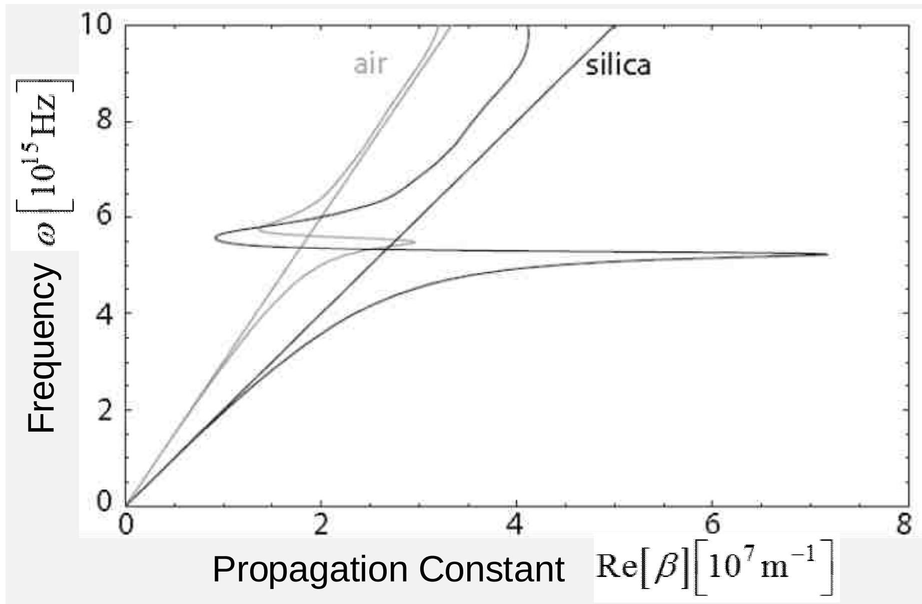
→ $\beta = \beta' - \mathrm{j}\beta''$

$$\beta' = \frac{\omega}{c_0} \sqrt{\frac{\varepsilon_1' \varepsilon_2'}{\varepsilon_1' + \varepsilon_2'}}$$

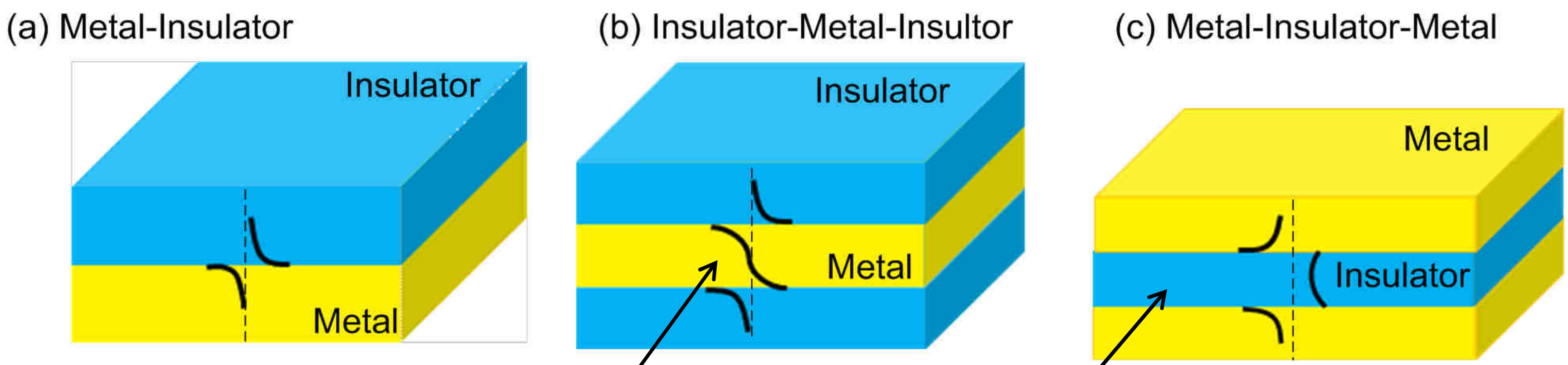
$$\beta'' = \frac{\omega}{c_0} \left( \frac{\varepsilon_1' \varepsilon_2'}{\varepsilon_1' + \varepsilon_2'} \right)^{3/2} \frac{\varepsilon_1''}{2\varepsilon_2'}$$

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

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



# Plasmonic Waveguides



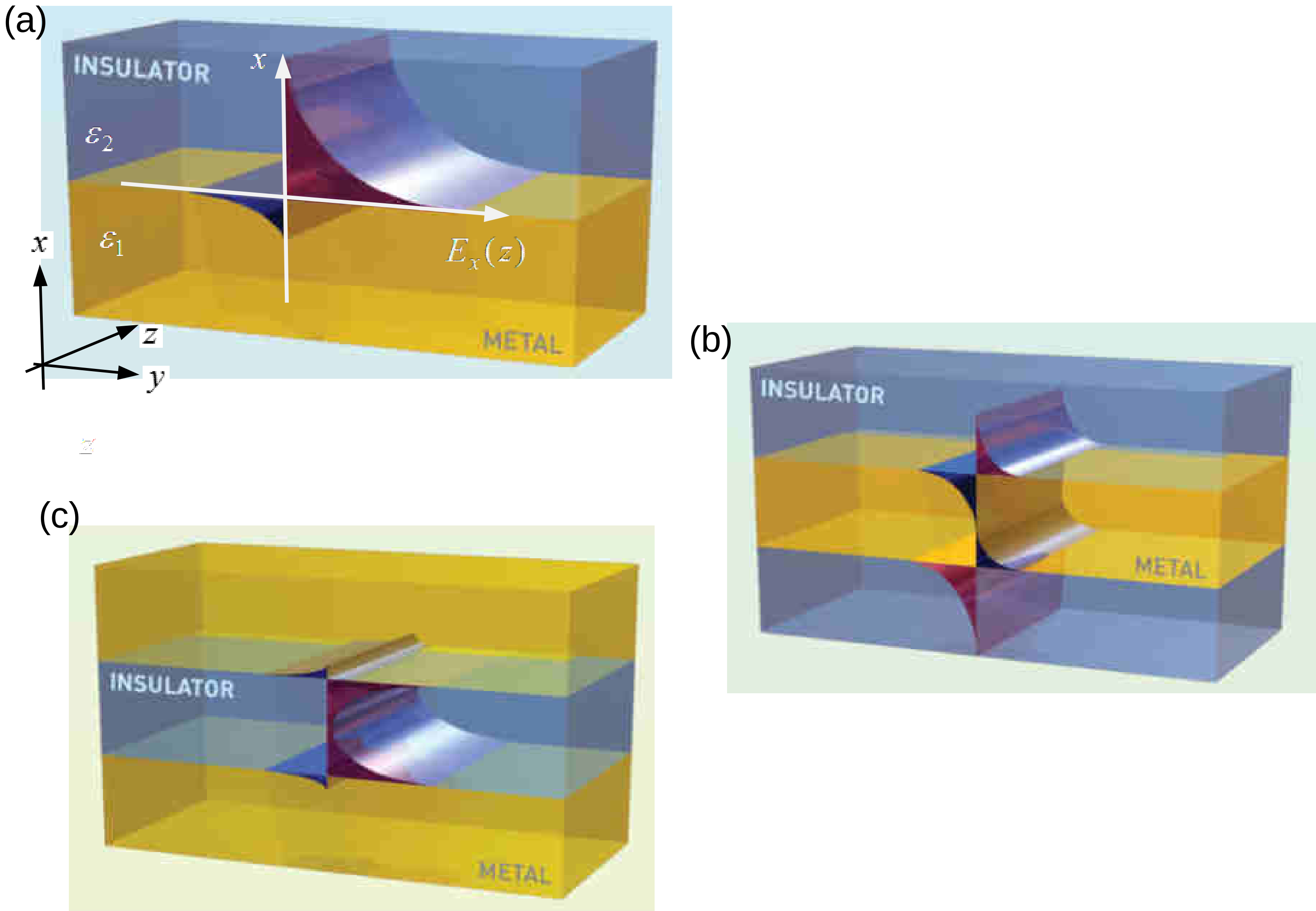

Good - simple

Long propgation

Good confinement
High loss

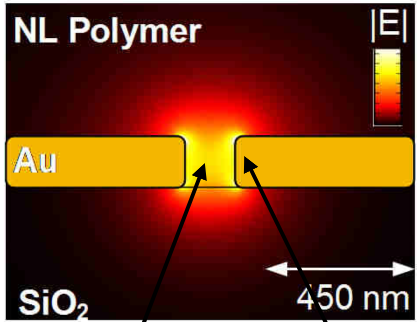
Ref.: “Plasmonic Communications”; Optics and Photonics News, May 2013

# Various SPP Waveguides



# Plasmons – Confinement to Small Space

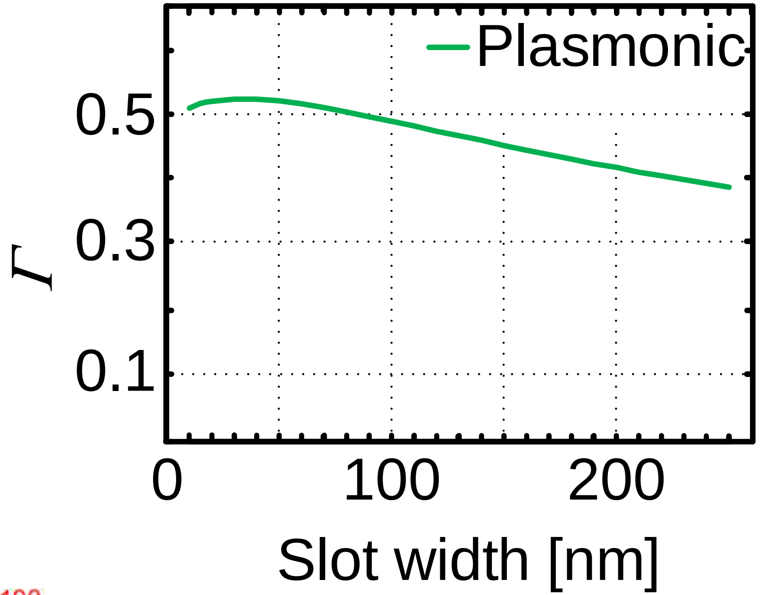
Optical Field



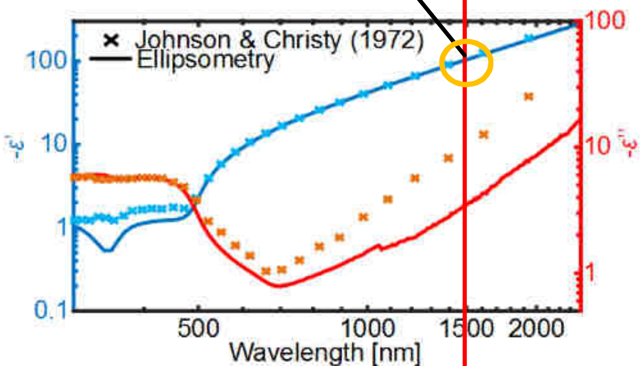

-40

$$E_{\mathrm{slot}} = \frac{\epsilon_{\mathrm{contact}}}{\epsilon_{\mathrm{slot}}} E_{\mathrm{rail}}$$

3



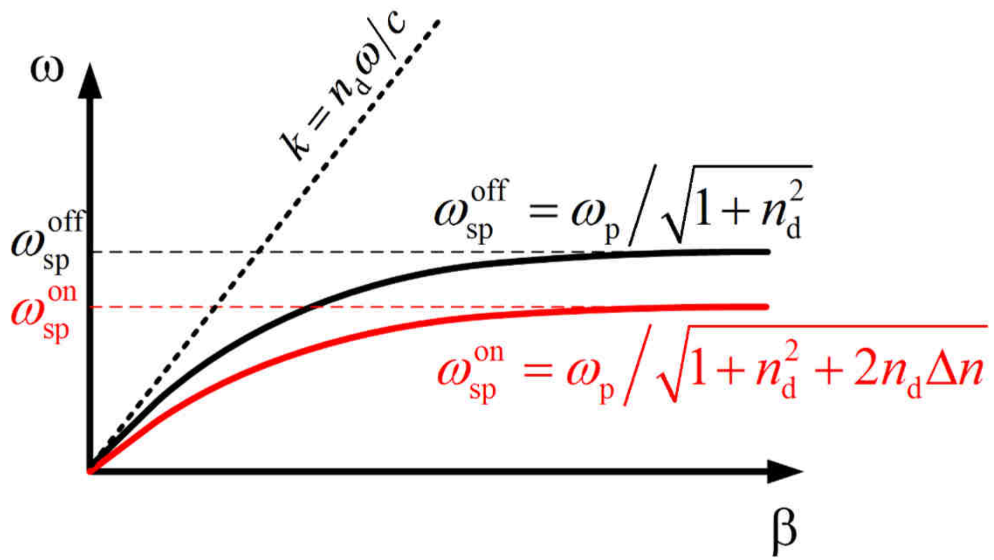

Gold

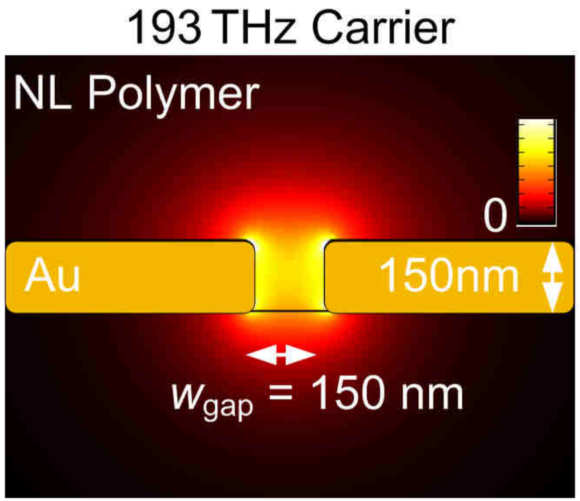



➔ Ideal to detect molecules at a surface

Haffner, C. *et al. Nature Phot.*, **(2015)**

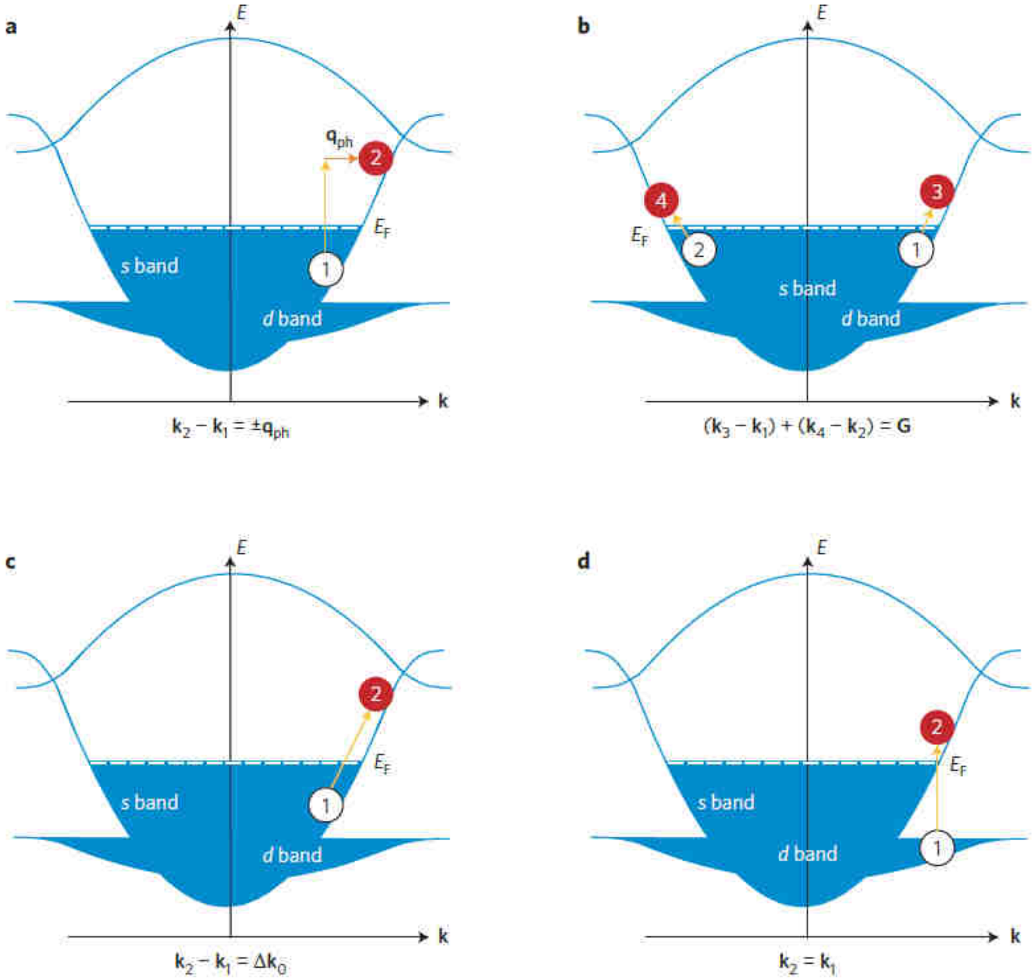
# Plasmons – Sensitive to Refractive Index



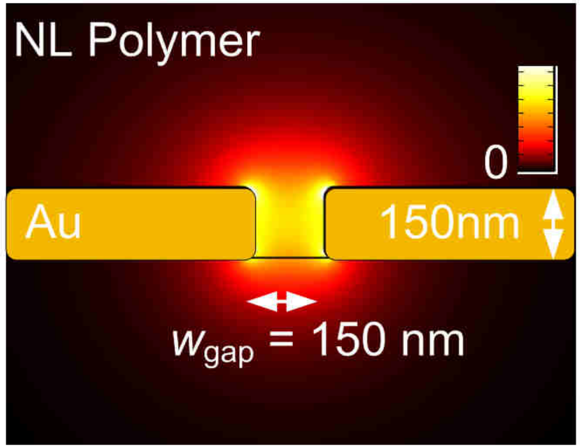




➔ Sensitive to refractive index changes

# Plasmons – High Losses




193 THz Carrier




➔ Only good if small!

J. B. Khurgin, "How to deal with the loss in plasmonics and metamaterials," Nat Nano **10, 2-6 (2015).**

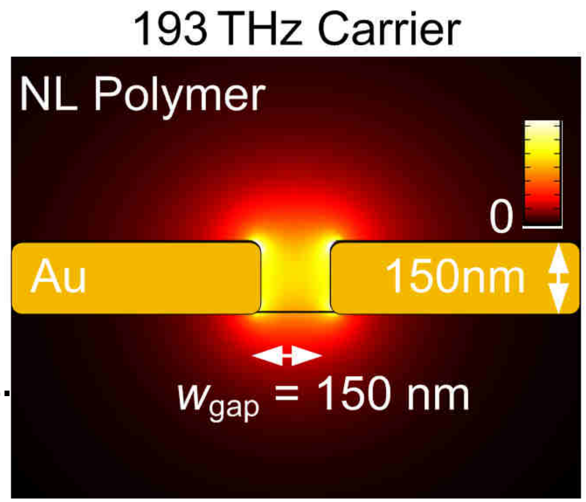
# Content

- A Metamaterial Mid-IR Emitter
- Surface Plasmon Polaritons (SPPs)
- A SPP interferometric detector

# Metal Organic Hybrid (MOH) Modulator

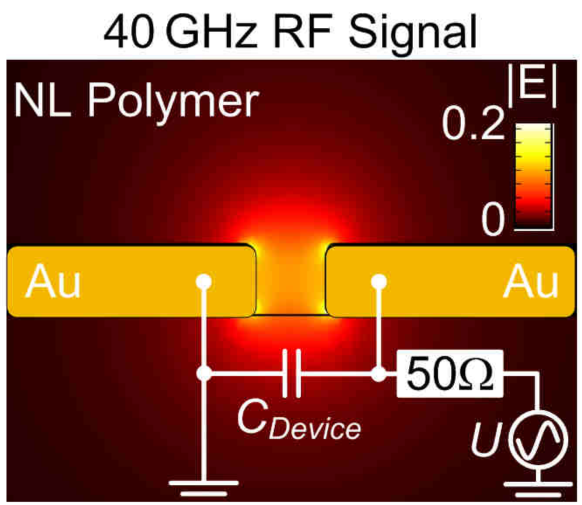
**High Efficiency, Ultra-compact**

1. Perfect overalp between
   - Optical mode
   - RF signal
2. Freedom to choose a nonlinear electro-optical mat.




**Ultra-fast**

- Instantaneous Pockels effect:
- Small RC-time constant



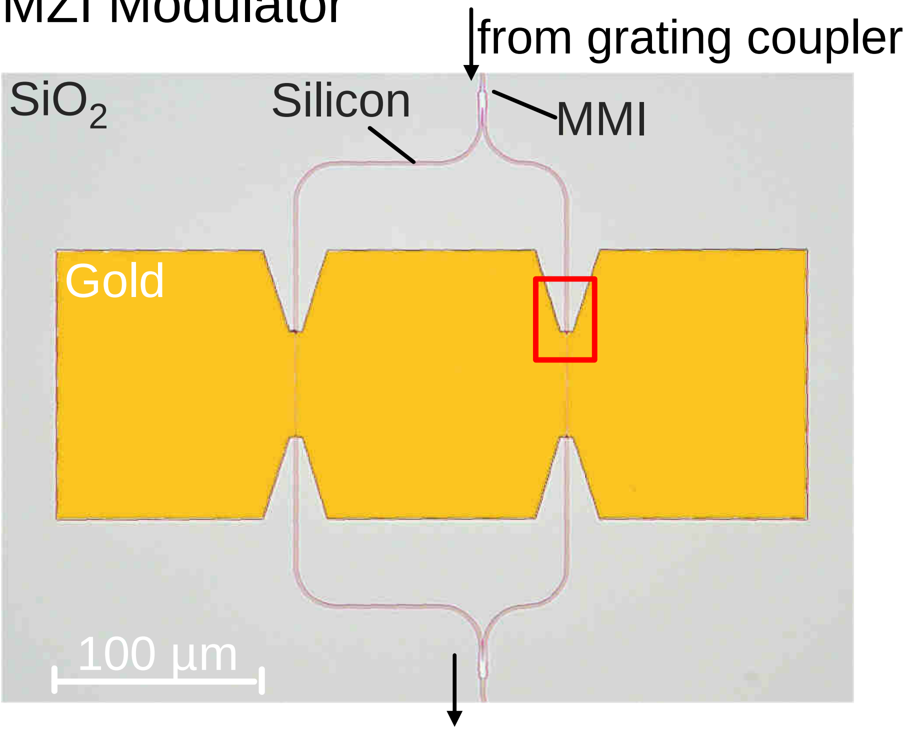

**Energy-efficient**

- Small $V_\pi$ & small capacitance

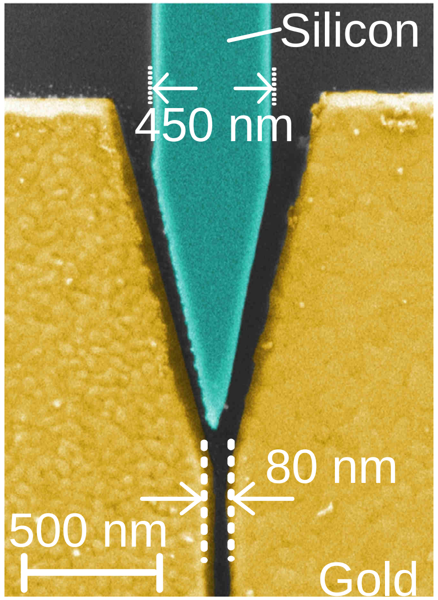
**Disadvantage:** High losses

# Plasmonic-Organic Hybrid Modulator

MZI Modulator




Photonic-plasmonic converter



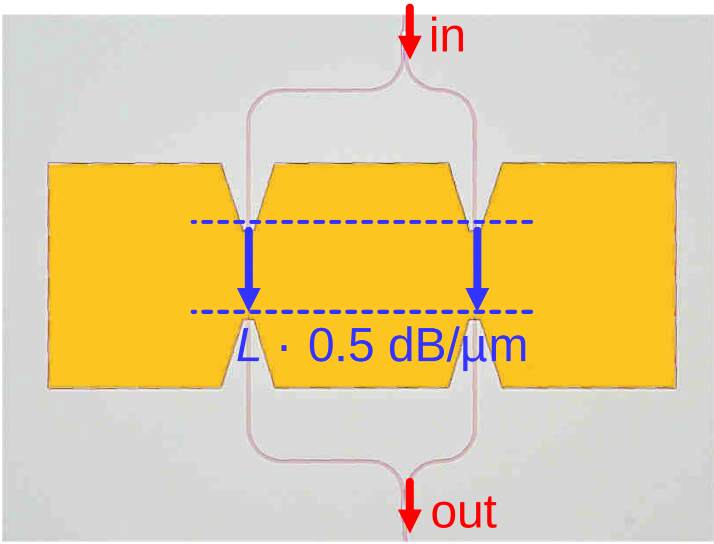

Mach-Zehnder Interferometer
- Low-loss silicon waveguides
- Plasmonic phase modulators

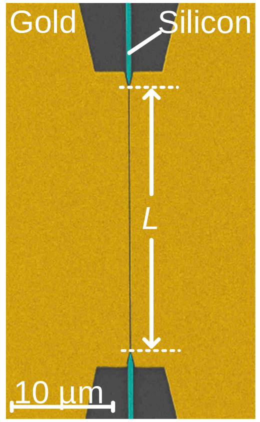
Photonic-plasmonic converter[4]
- From 450 nm to 80 nm

Ref. W. Heni, Proc. OFC'2015

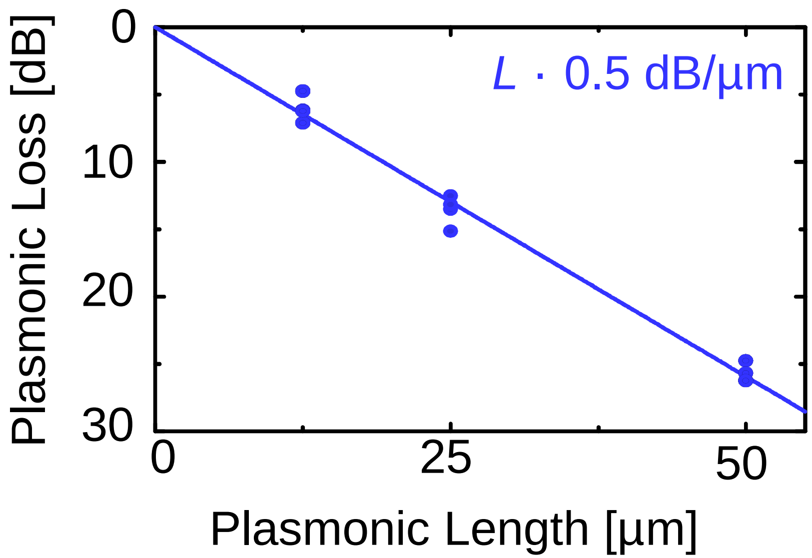
4. Tian et al. Appl. Phys. Lett. **95,** 013504, 2009

# Device Characterization: Optical Losses



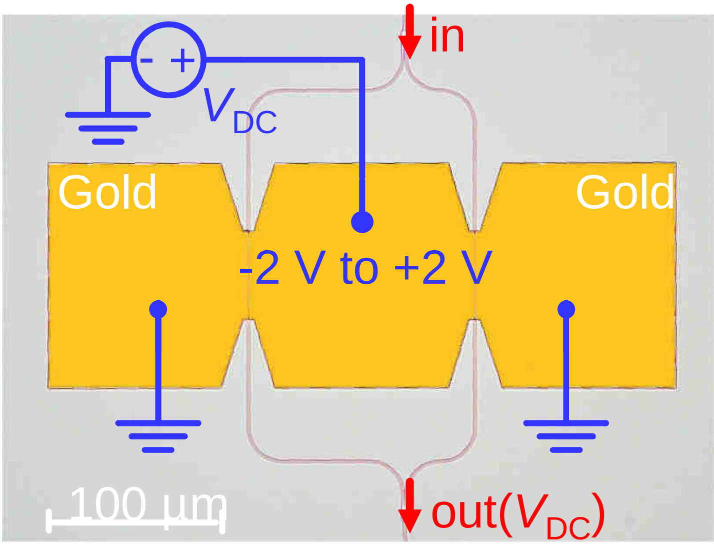



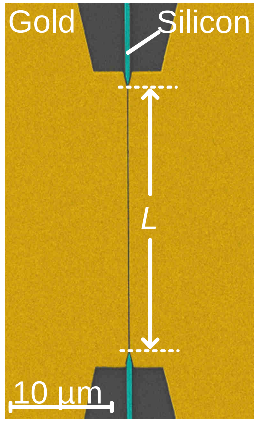

- Low loss plasmonic waveguides
    - High gold quality
    - High quality fabrication process
    - Low sidewall roughness

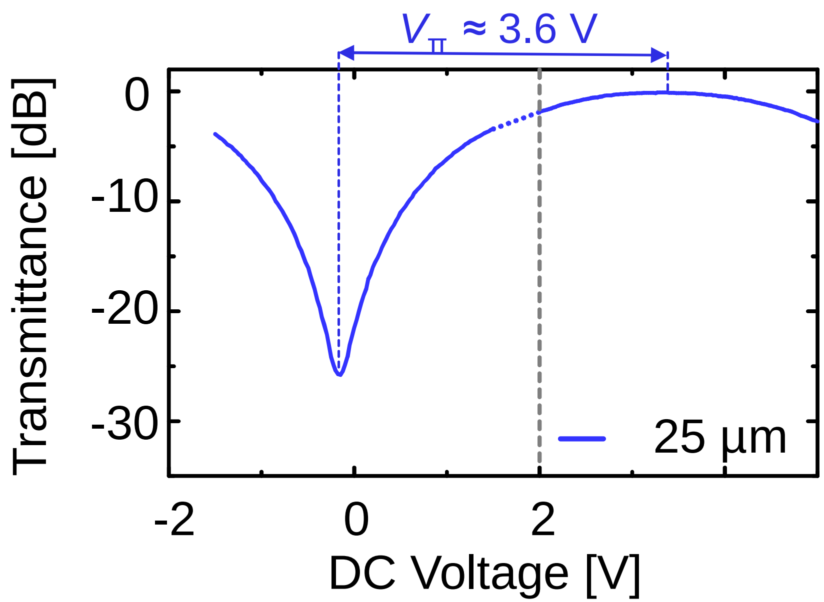



Ref. W. Heni, Proc. OFC'2015

# Device Characterization: Extinction



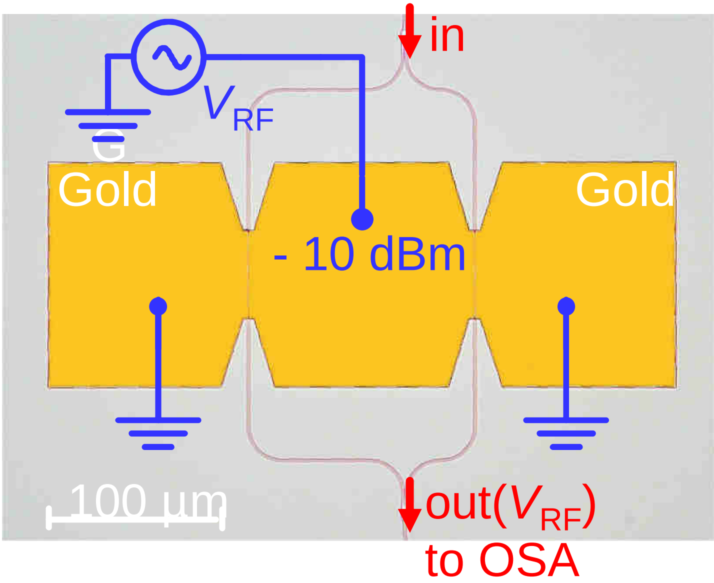



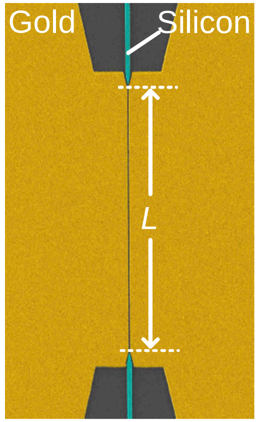




- High-quality plasmonic waveguides
  - Extinction Ratio > 25 dB
  - $V_\pi \approx 3.6$ V
  - $V_\pi L \approx 90$ Vµm

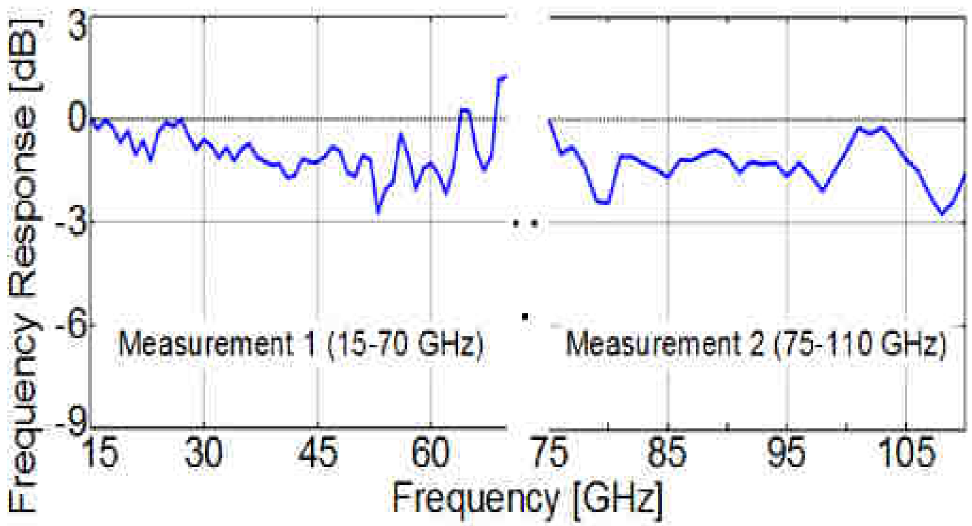
Ref. W. Heni, Proc. OFC'2015

# Device Characterization: Frequency Response



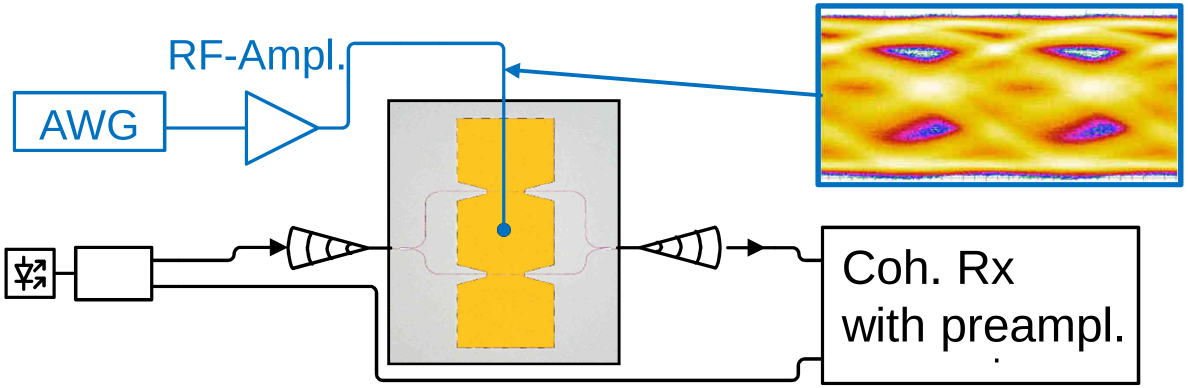




- Electrical Bandwidth > 105 GHz
- Optical Bandwidth > 100 nm

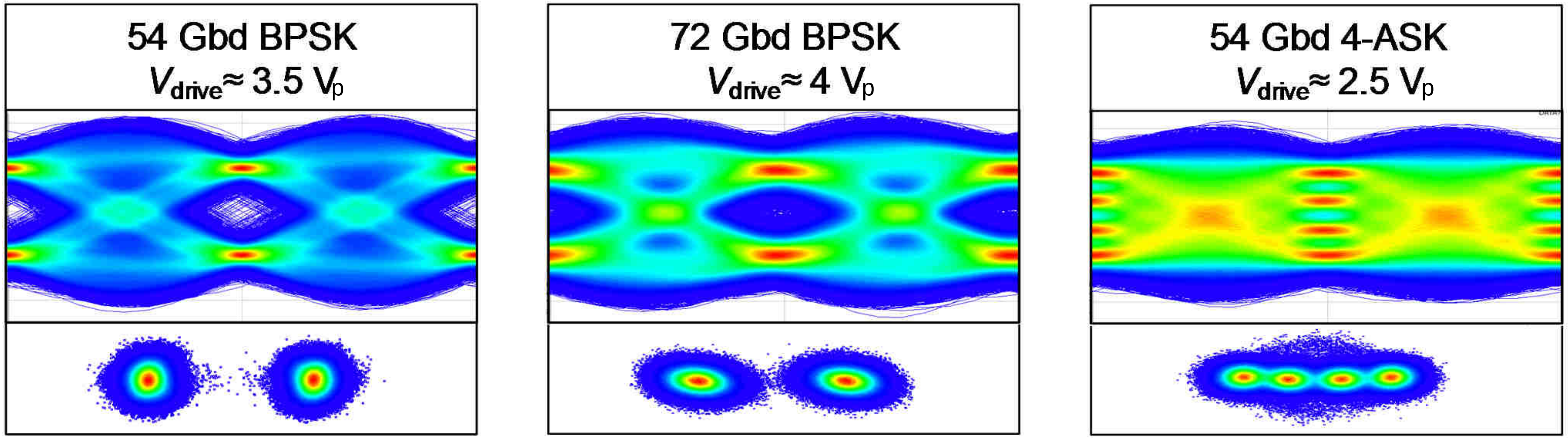



Ref. W. Heni, Proc. OFC'2015

# Data Experiments




**Line rate: 108 Gbit/s**
(FEC, 20 % overhead)*



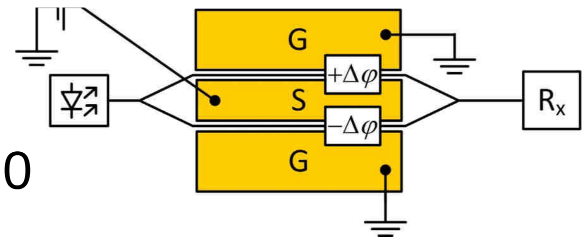

BER = $1.9 \times 10^{-6}$ BER = $3.5 \times 10^{-5}$ BER = $1.8 \times 10^{-2}$

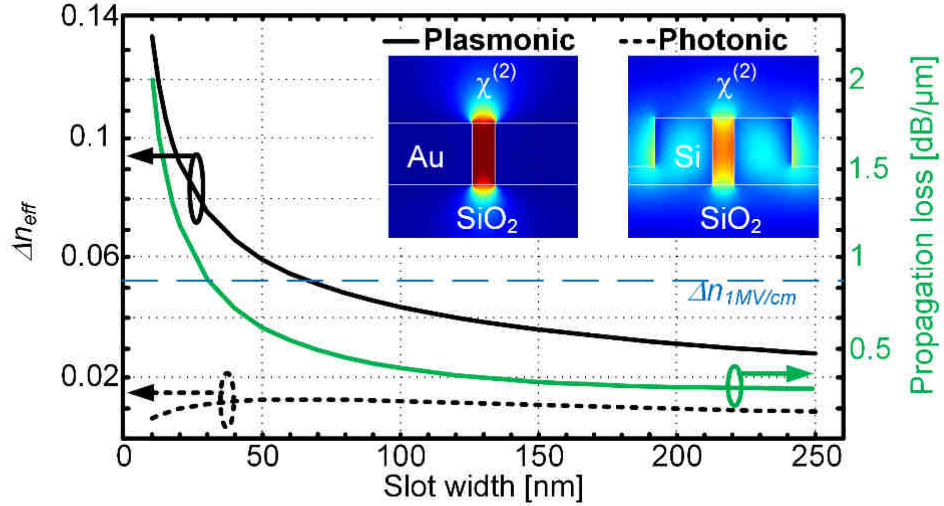
Limited bandwidth of RF components:
Pre-distortion (54 Gbd) and post-equalization (54 Gbd, 72 Gbd)

Ref. W. Heni, Proc. OFC'2015

# Origin of Large Linear Electro-Optic Effect

- The configuration: MZI gives a factor 2
- Short & open Circuit: MZI gives a factor 2
- The plasmonic configurations adds a factor 10



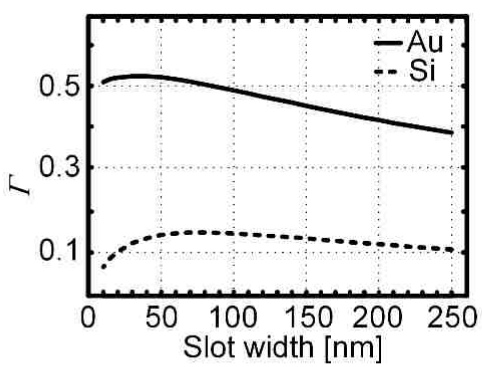



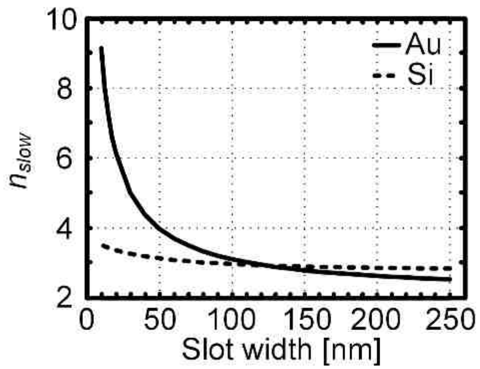

$$\Delta n_{\mathrm{eff}} \cong \Gamma \cdot \frac{\Delta n_{\mathrm{mat}}}{n_{\mathrm{mat}}} \cdot n_{\mathrm{slow}}$$

Plasmonic Confinement

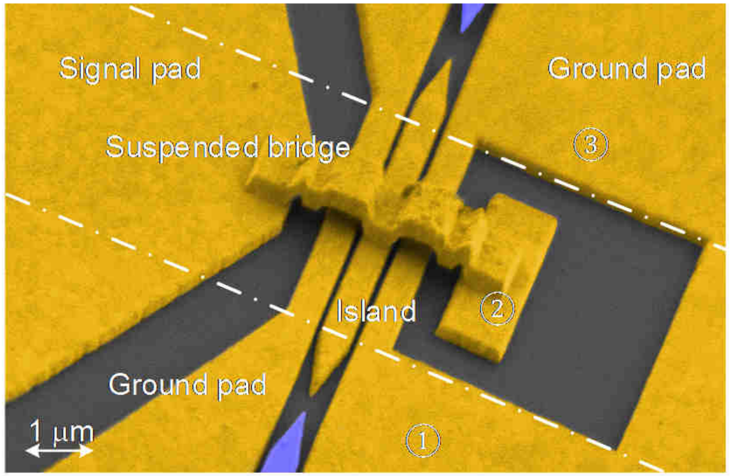
Large Electro-Optic Effect

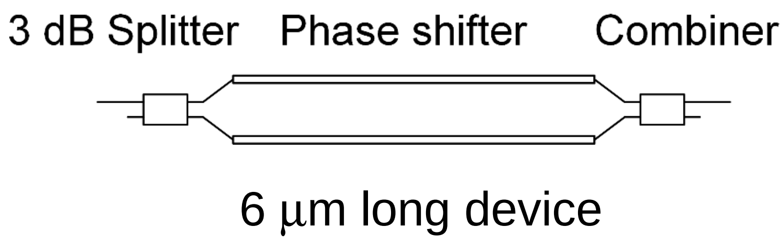
Plasmonic Slow-Down Effect

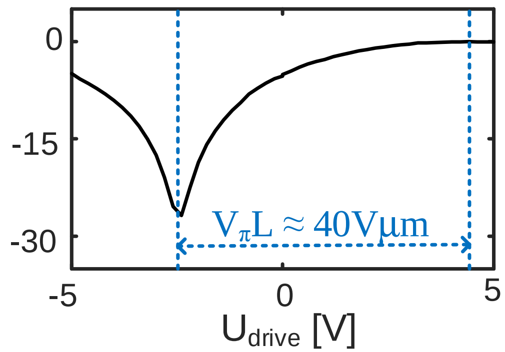


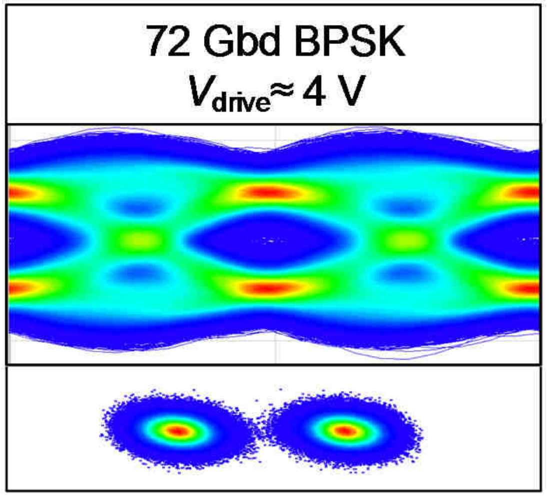



# All-Plasmonic MZM



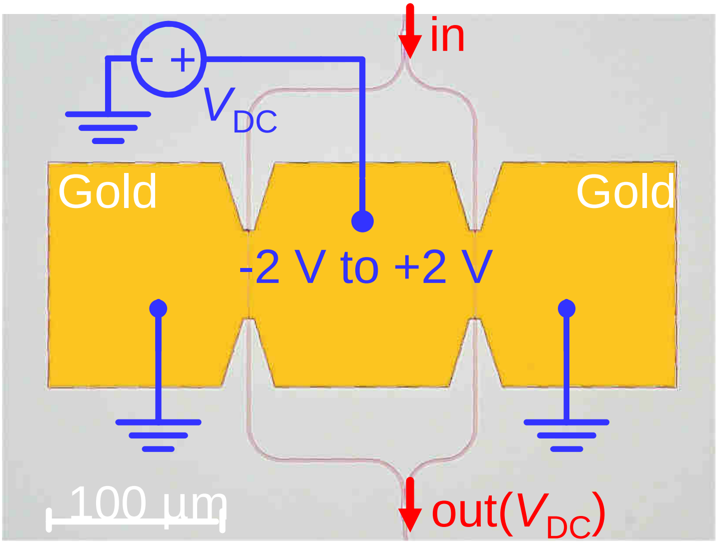



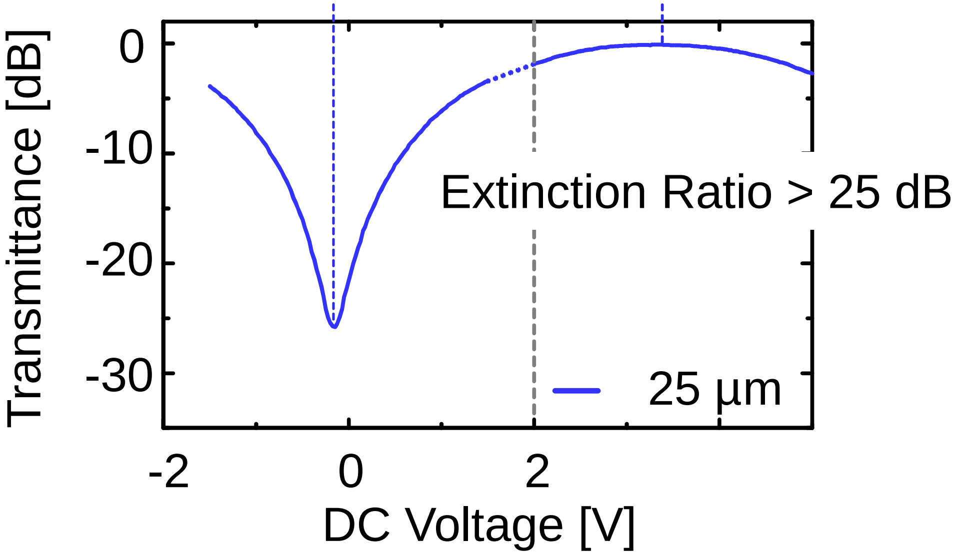

Haffner, C. *et al. Nature Phot.*, **(2015)**

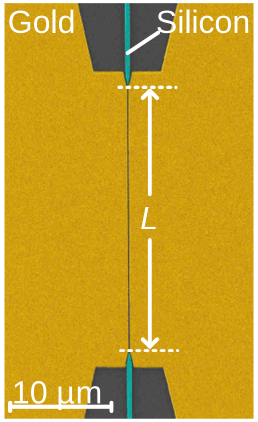
Plasmonic MZM

- Record footprint (10 x 1.5µm$^2$)
- Speed – among the best 72 GBd
- World record 20 fJ/bit @ 72 GBd
- Chip-losses of 8 dB

# A Sensitive Interferometer for Bio-Applications?




Functionalize one arm → Sensitive to phase changes

Ref. W. Heni, Proc. OFC'2015

# Thank you