M. Midrio, D. Truccolo
Università degli Studi di Udine

# Efficient antennas and rectifying ballistic diodes for harvesting of solar energy

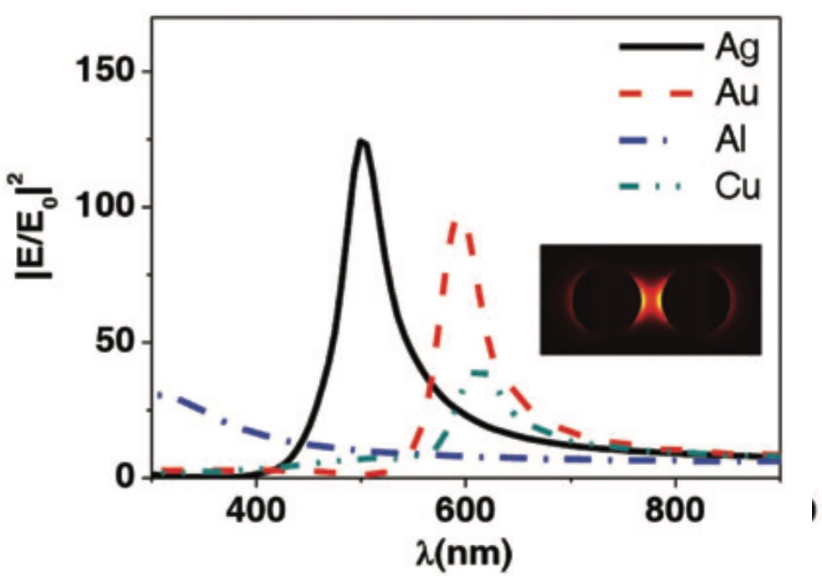
M. Midrio, D. Truccolo
Università degli Studi di Udine

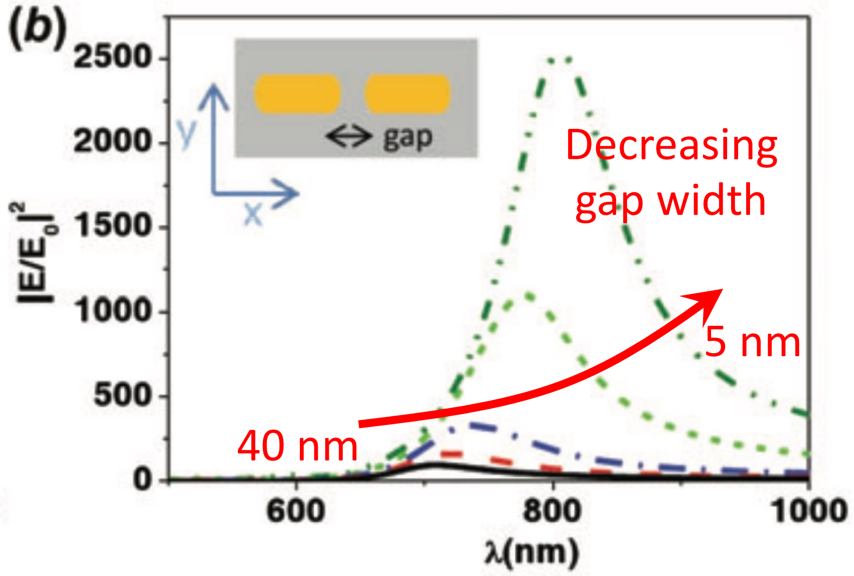
- Some common (mis)concepts on optical antennas and antenna efficiency measurements
- The design of an antenna array with high efficiency
- The ballistic diode

# Some common (mis)concepts on optical antennas

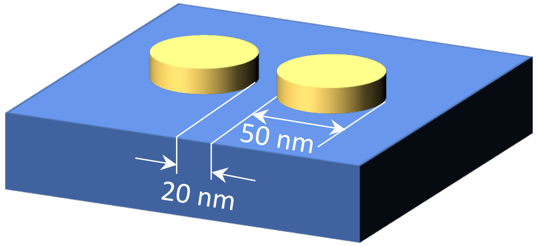
"The beauty of optical antennas is the
strong field enhancement between the terminals"

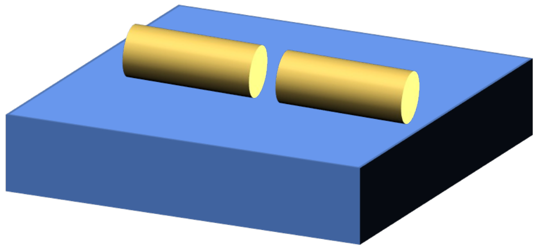
- **Can antennas providing large field enhancement really be used for energy harvesting?**
- **Is field enhancement so important for energy harvesting?**




Roberto Fernández-García et al., Design considerations for near-field enhancement in optical antennas, **Contemporary Physics**, vol. 55, 2014, issue 1



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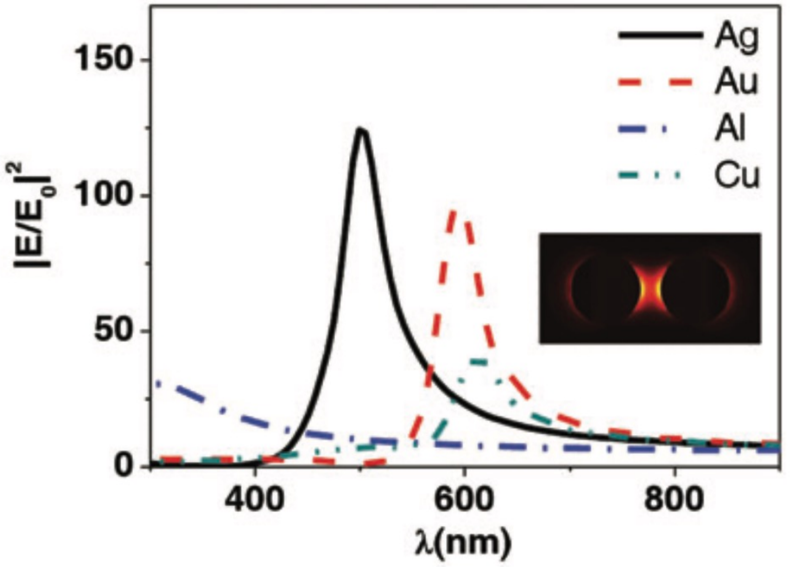


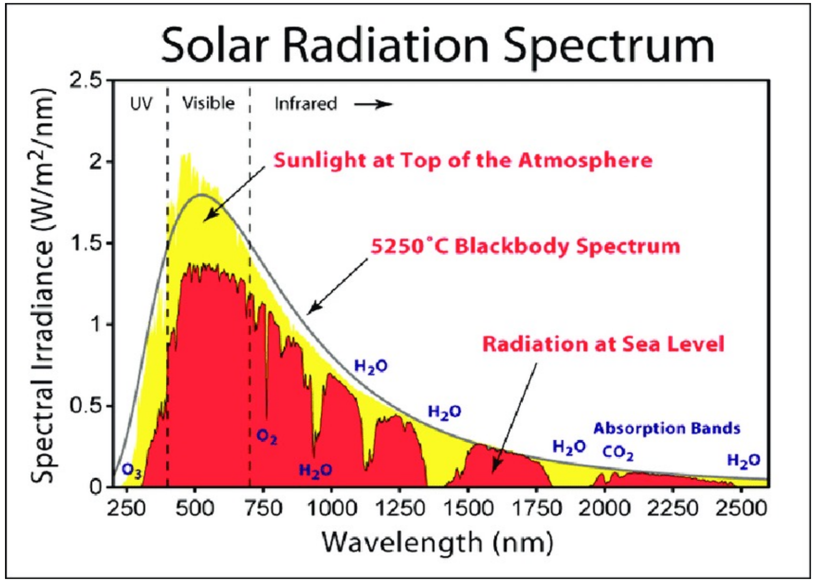


Usually, enhancement is intrinsically related to some resonance … and therefore is a NARROWBAND process
… are we sure we're doing the right thing for harvesting of sunlight?

# Some common (mis)concepts on optical antennas

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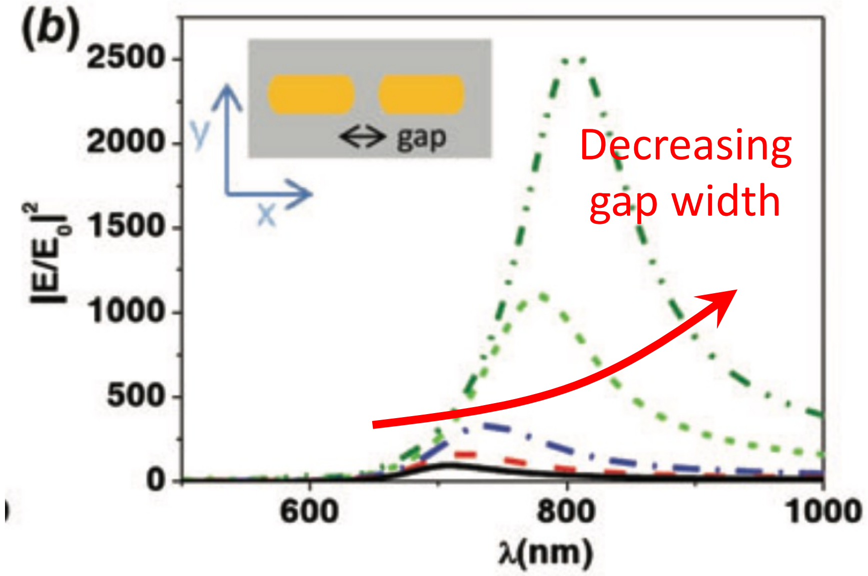
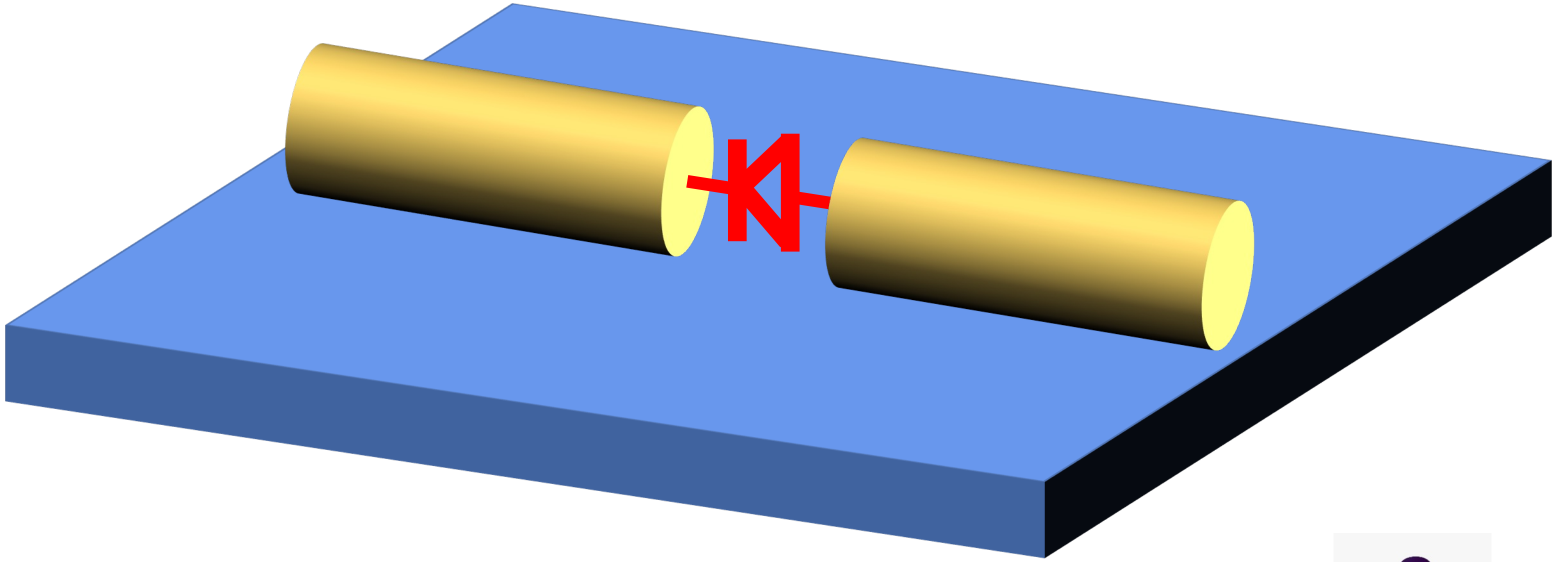


Roughly speaking, when one halves the gap width the field between terminals doubles

$$V_{terminals} = \int_{gap} \vec{E} \cdot \overrightarrow{dl} = constant$$

# The GreEnergy approach

1. The role of our antennas is that of converting sunlight into DC current/voltage through a diode. Therefore

    a. The key-performance-indicator is not the field enhancement; rather, we look for the ability to deliver power to the load (diode);

    b. antennas must be broadband, dual-pol and “insensitive” to the angle of arrival of sunlight;

2. We need to exploit the physical space as well as we can. We do not design a single antenna and hope for a stroke of luck when we pack antennas: we start from the design of a lattice of antennas.

# Some more (mis)concepts on optical antennas

## Measurement of antenna efficiency
## State of the art prior to GreEnergy Project

How does one measure the efficiency of an antenna?

- Transmitting vs receiving efficiency

- A real flaw: greater than 50% efficiency
  with no reflecting ground???

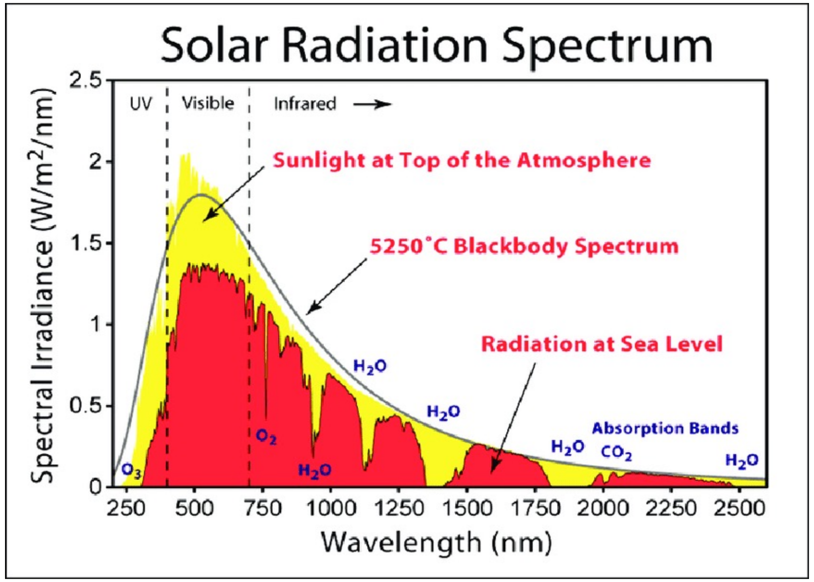
# Some more (mis)concepts on optical antennas

## Measurement of antenna efficiency
## State of the art prior to GreEnergy Project

The definition of antenna efficiency

$$\eta_{TOT} = \frac{\int P(\lambda)\eta_A(\lambda)d\lambda}{P(\lambda)d\lambda}$$

$$\eta_A(\lambda) = \begin{cases} \dfrac{P_{RAD}(\lambda)}{P_{RAD}(\lambda)+P_{LOSS}(\lambda)} & \text{“Transmitting efficiency”} \\ \dfrac{P_{LOAD}(\lambda)}{P_{INCIDENT}(\lambda)} & \text{”Receiving efficiency”} \end{cases}$$

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RAPID COMMUNICATION

**Upper bounds for the solar energy harvesting efficiency of nano-antennas**


Guy A.E. Vandenbosch*, Zhongkun Ma


**“Record” efficiency equal to 59.6%**

# Some more (mis)concepts on optical antennas

Measurement of antenna efficiency

State of the art prior to GreEnergy Project

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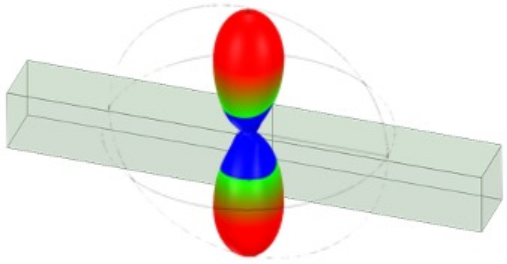

**Problem #1. Source impedance (or load) has no role?**

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Measurement of antenna efficiency - State of the art prior to GreEnergy Project

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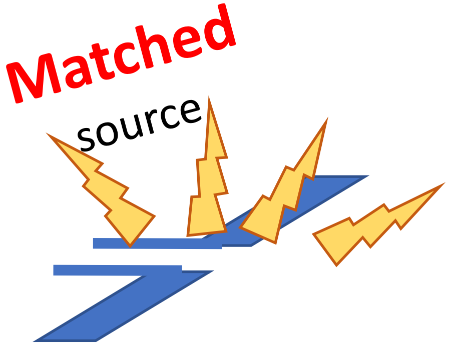
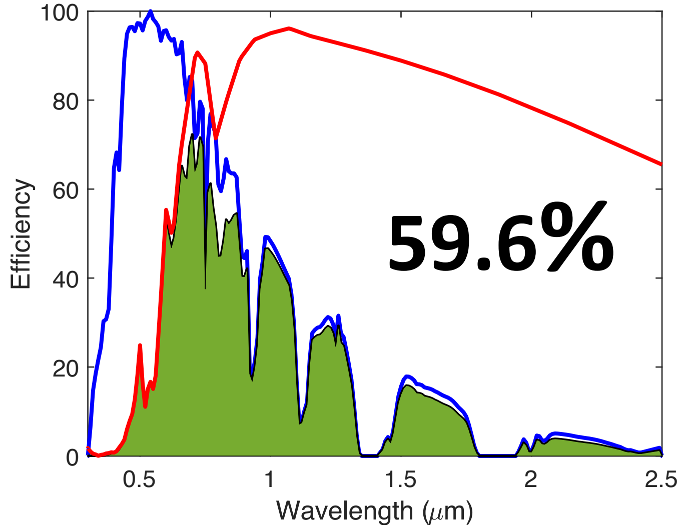
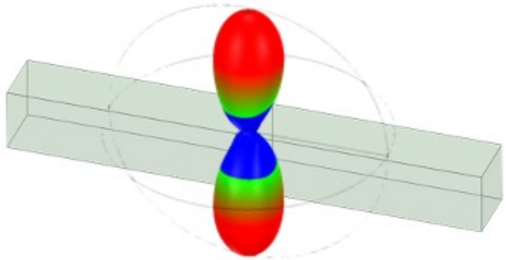



***Transmitting* efficiency**



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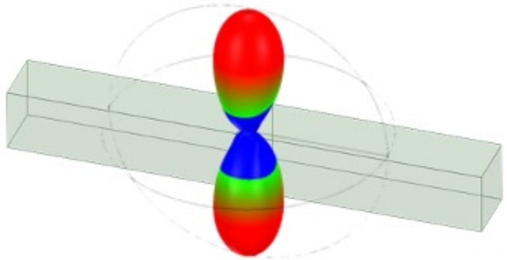

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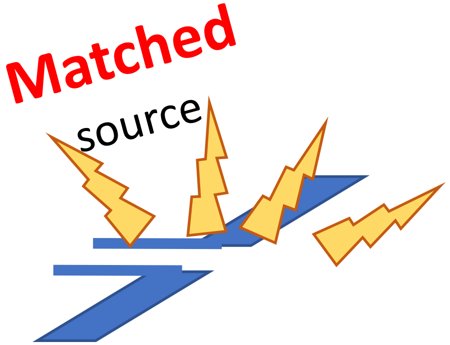
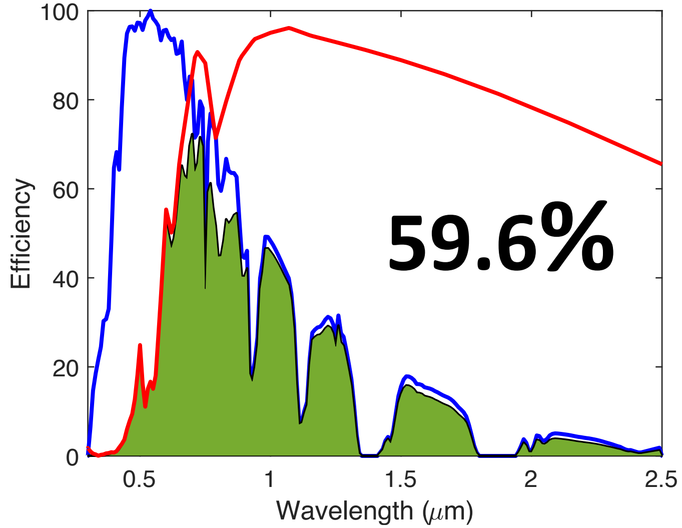
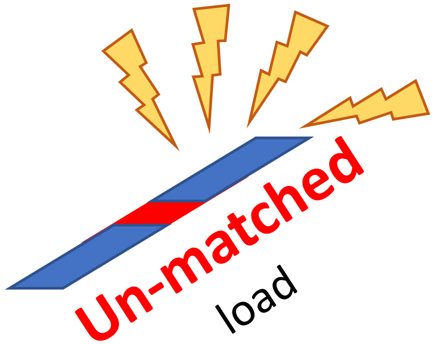
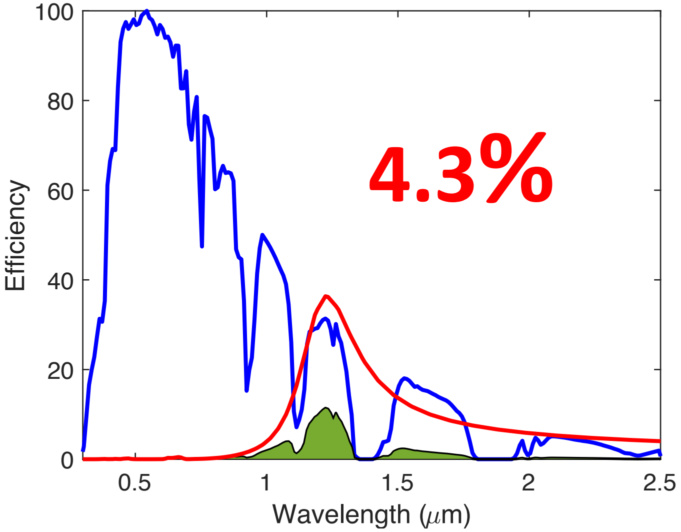



***Transmitting*** **efficiency**




***RECEIVING*** **efficiency**



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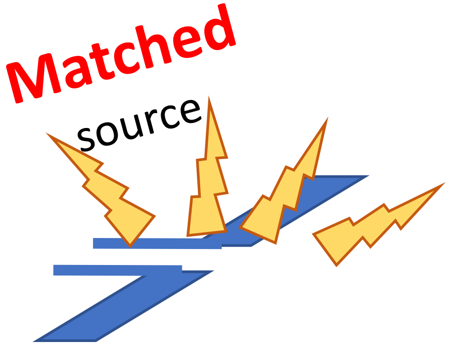
Measurement of antenna efficiency - State of the art prior to GreEnergy Project

**Transmitting vs receiving efficiency**

$$\eta_A(\lambda)=\begin{cases}\dfrac{P_{RAD}(\lambda)}{P_{RAD}(\lambda)+P_{LOSS}(\lambda)}\\[2ex]\dfrac{P_{LOAD}(\lambda)}{P_{INCIDENT}(\lambda)}\end{cases}$$

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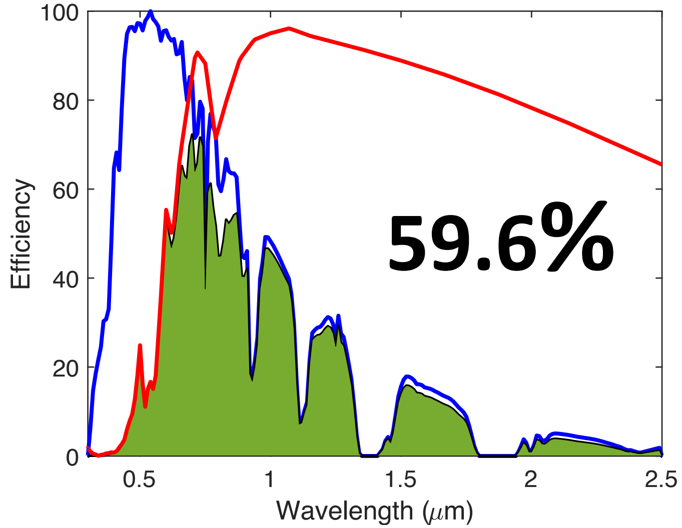


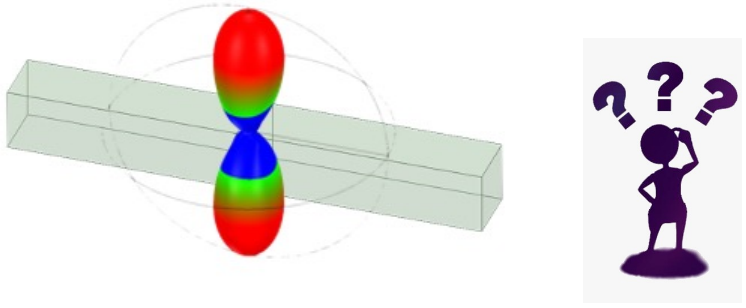

**Problem #2. Larger than 50% efficiency with a dipole in free space????**

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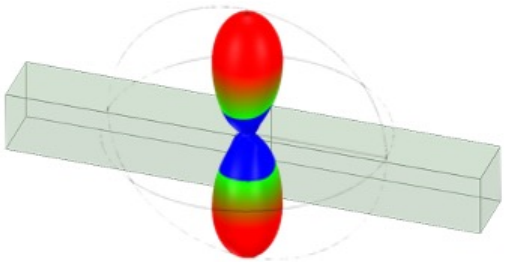


**Problem #2. Larger than 50% efficiency with a dipole in free space????**

**The receiving area of an array of antennas with no ground-plane is, at most, half its physical size** [J. Kraus, *Antennas* (New York: McGraw-Hill, 1950)]. **Read as: such an antenna can receive 50% of the incoming power at best.**

Let us see the practical implications of this property and the difference between transmitting and receiving efficiency.

Suppose an ideally lossless antennas fed by a perfectly matched source is considered.

**Transmitting efficiency**

$$\frac{P_{RAD}(\lambda)}{P_{RAD}(\lambda) + P_{LOSS}(\lambda)} = 100\%$$

**Receiving efficiency**

$$\frac{P_{LOAD}(\lambda)}{P_{INCIDENT}(\lambda)} = 50\%$$


Where is the missing 50%?

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## Measurement of antenna efficiency - State of the art prior to GreEnergy Project

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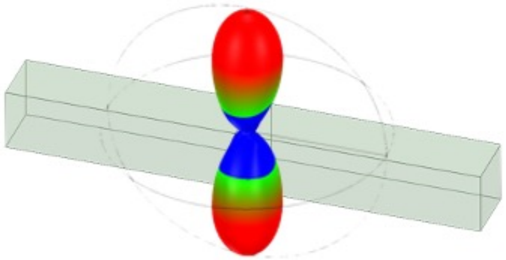

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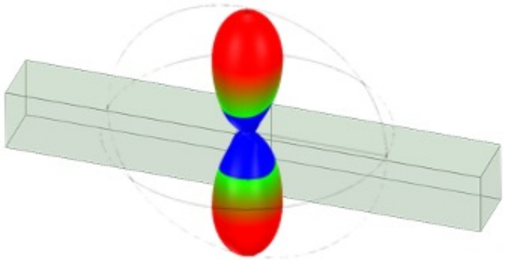
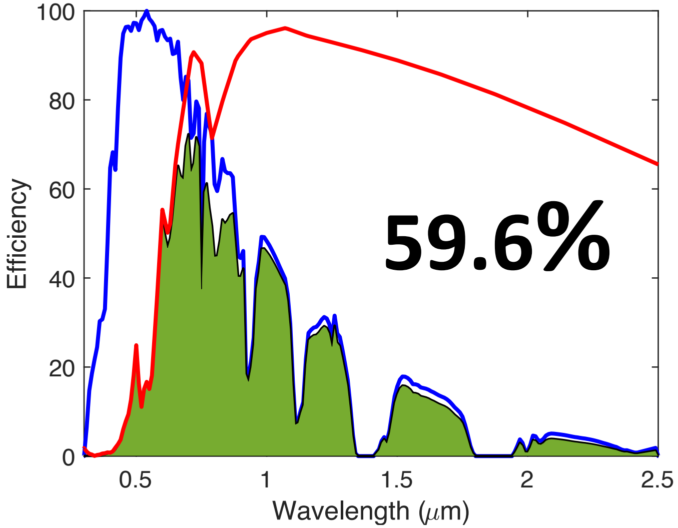
**The receiving area of an array of antennas and matched loads can equal its physical size only in the presence of a ground-plane** [S. A. Schelkunoff and H. T. Friis, Antenna Theory and Practice (John Wiley and Sons, 1952)]



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By NO MEANS can an antenna like this (that is: with no ground plane) have a “real” (receiving) efficiency larger than 50%.

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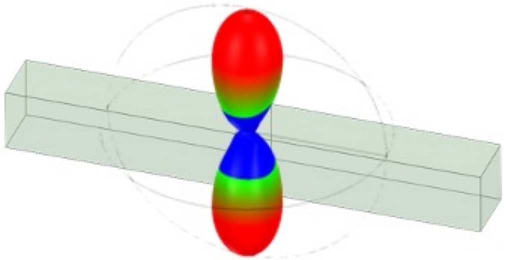

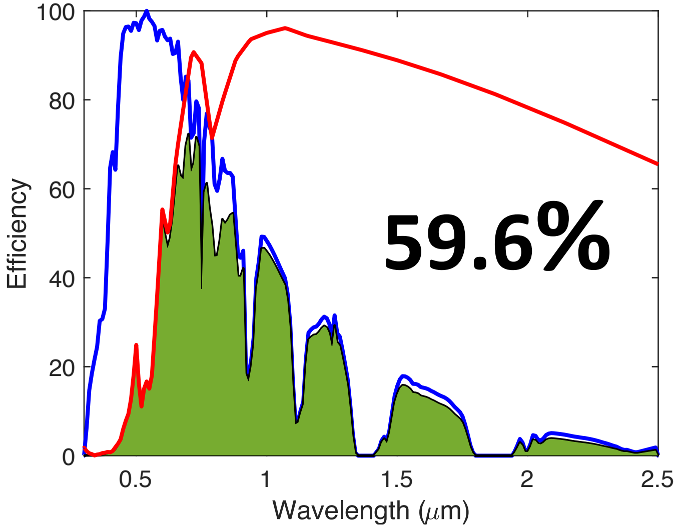


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# Guidelines in GreEnergy approach

**Maximization of (receiving) efficiency**

1. Antennas need to have a backreflector

**Broadband behaviour**

US Patent US3789404A, B. A. Munk, "Periodic surface for large scan angles":

1. In order for any periodic surface to have a stable resonant frequency with angle of incidence, the interelement spacings must be small ($< 0.4\lambda$)

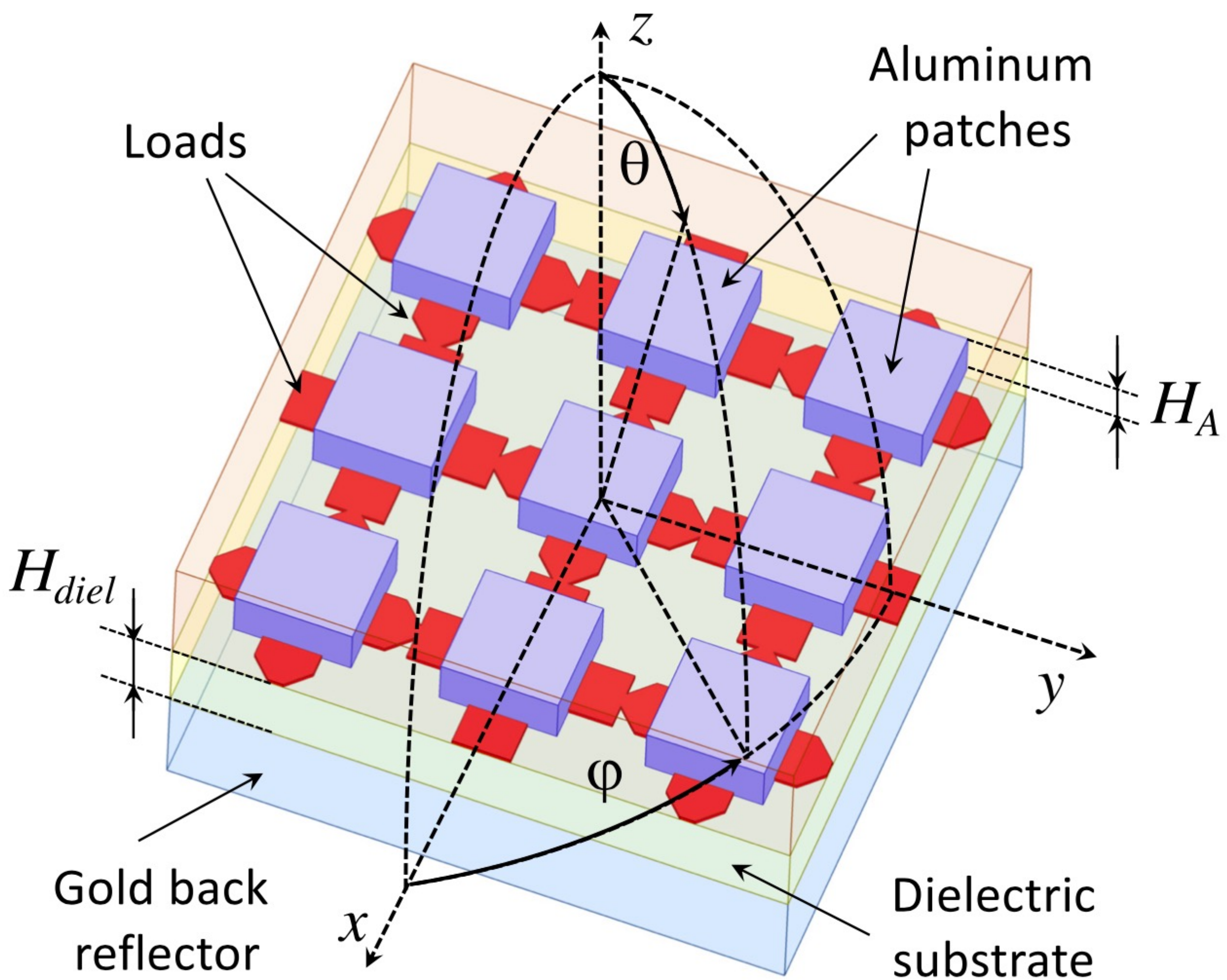
2. Adding dielectric slabs on the outside of all narrow-band devices can reduce the typical bandwidth variation from as much as 6.5: 1 to less than 1.5:1 (for angle of incidence up to $70^o$, any polarization)

    - A completely general rule can not be found, but typical values of slab dielectric constant $\varepsilon$ should be $< 1.6$ and with a thickness of about $0.25\lambda$

**Dual polarization**

1. A bit of physical intuition and fantasy

# The GreEnergy proposed solution




- Small interelement spacing (140 nm pitch)
- Backreflector!
- Extremely careful optimization of dimensions, thicknesses, choice of materials

# The GreEnergy proposed solution

## Broadband behaviour

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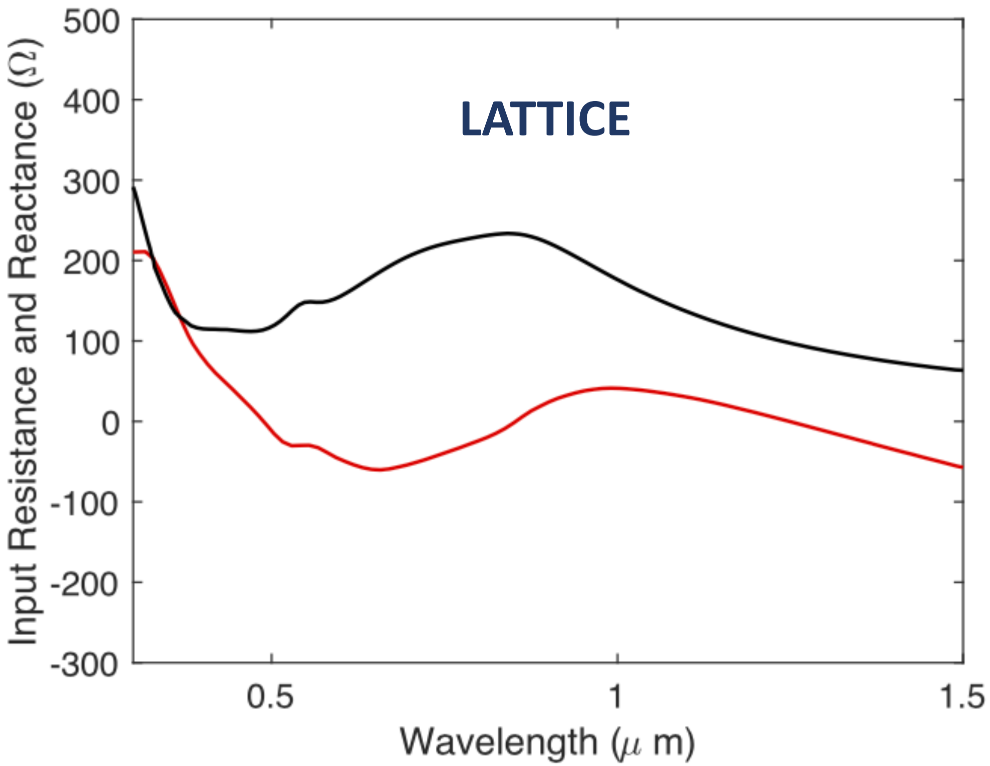


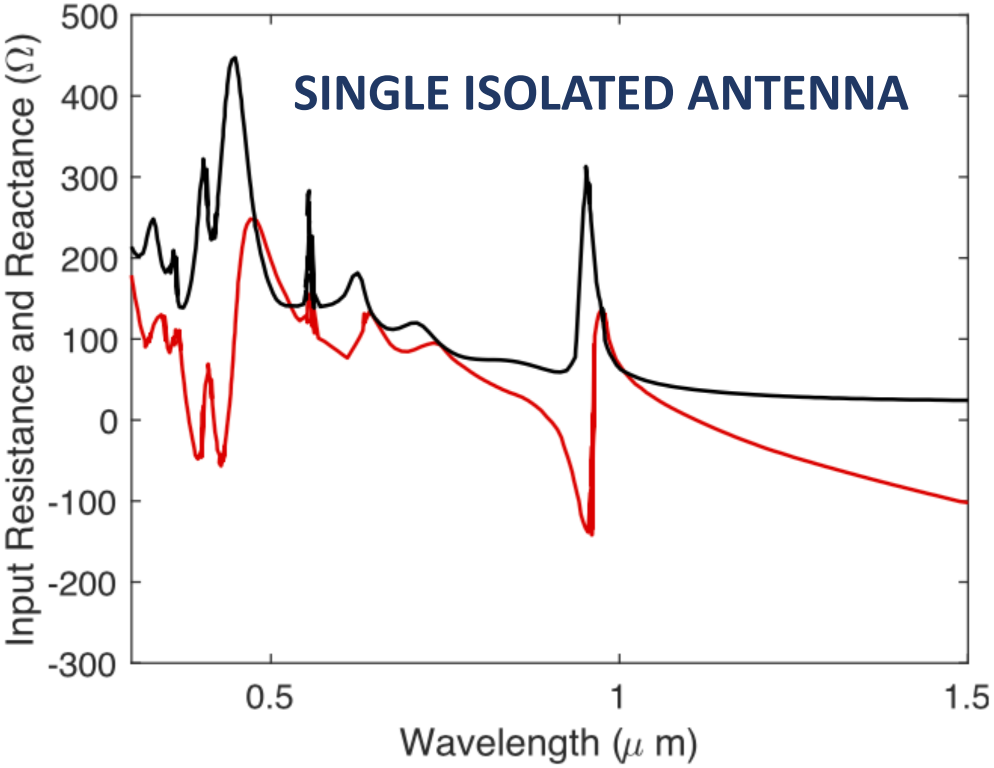

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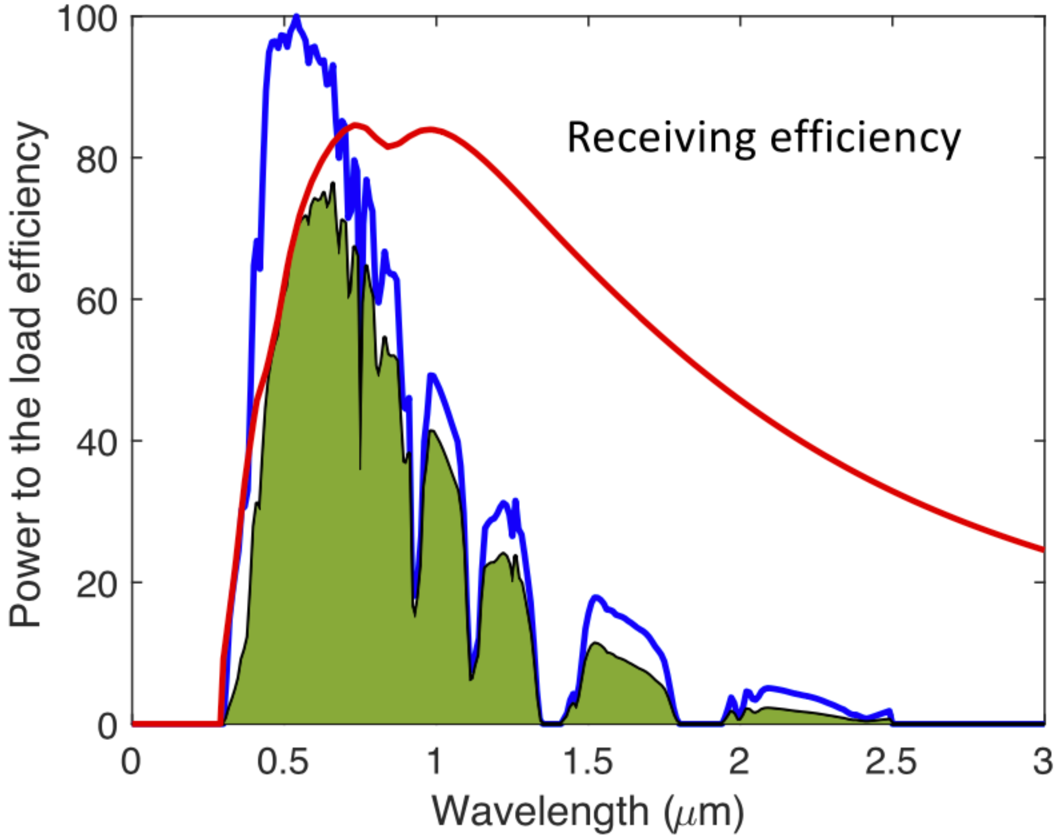


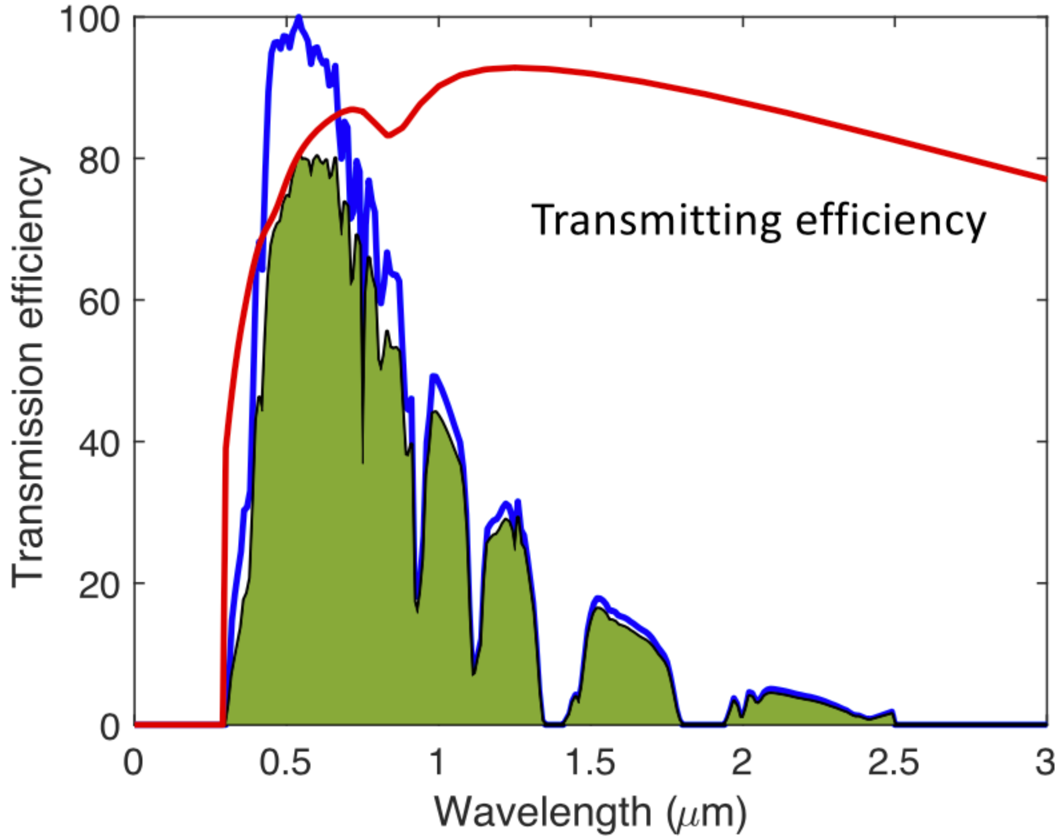

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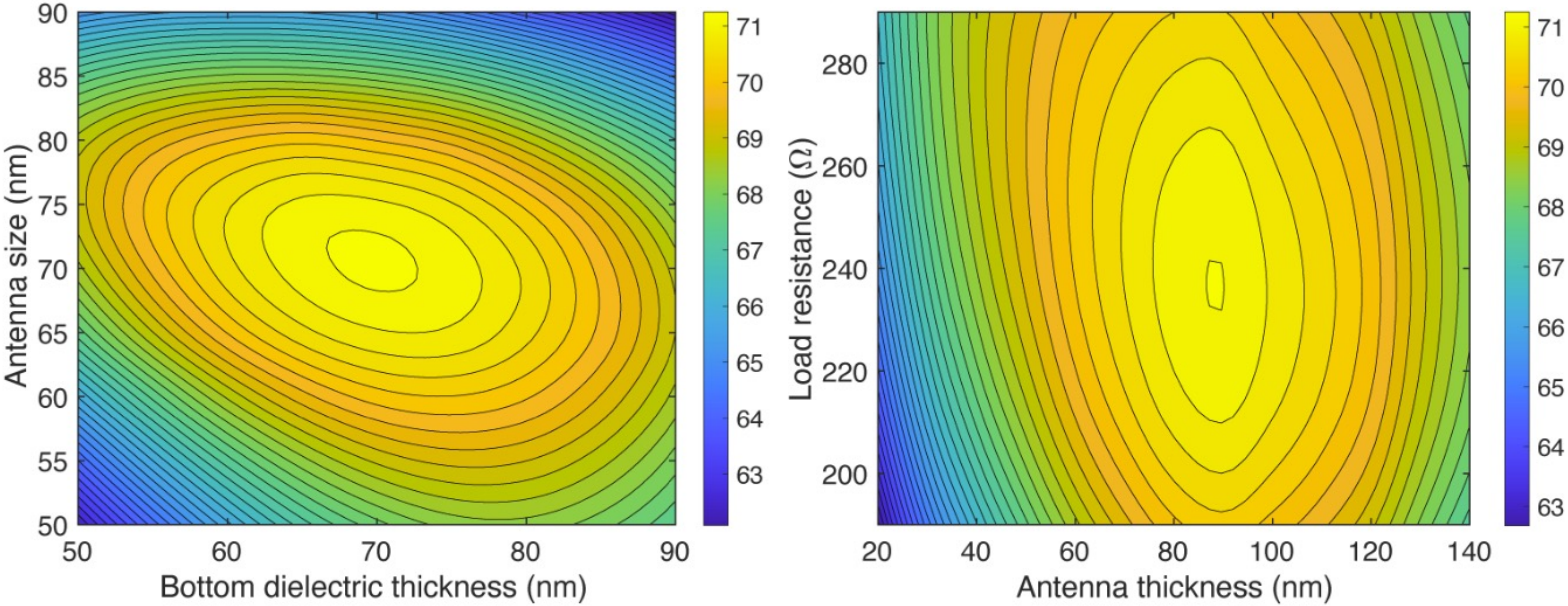
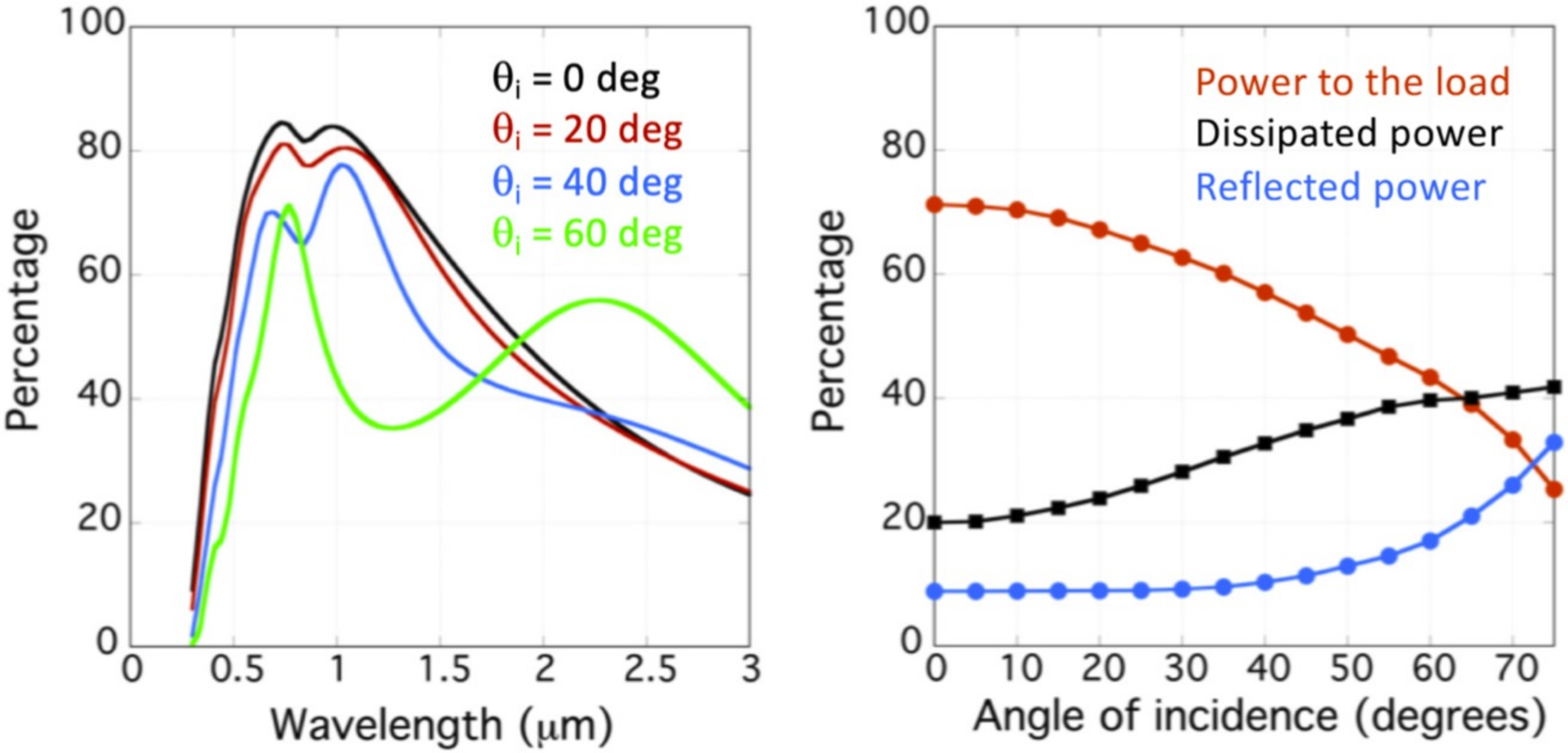



World record, 71.2% receiving efficiency

# The GreEnergy proposed solution




Decently stable vs. angle of arrival

M. Midrio, D. Truccolo
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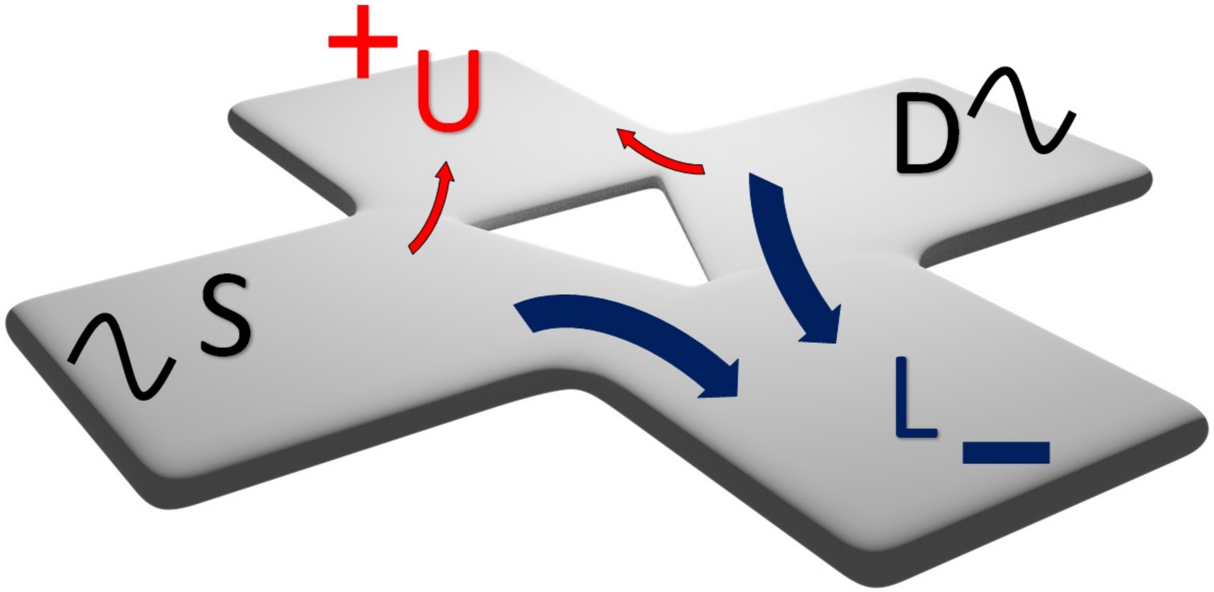
- Some common (mis)concepts on optical antennas and antenna efficiency measurements
- The design of an antenna array with high efficiency
- **The ballistic diode**

# Introduction: Graphene ballistic rectifier

- Graphene structures cross-shaped with a triangle etched at the center

- An AC signal between S and D induces a voltage $V_{LU}$ having a non null DC component ➔ rectification

- For simply geometrical reasons electrons injected at S and D move easier to the L compared to the U terminal




- Rectification is thus a non-linear effect arising from geometrical features and it is favoured by ballistic transport conditions [1]

[1] Song, A. M. (1999). Formalism of nonlinear transport in mesoscopic conductors. Physical review B, 59(15), 9806.

# Introduction: Graphene ballistic rectifier

No built-in potential

No threshold voltage → small signal rectification

No parasitic capacitance → High frequencies rectification

Energy harvesting applications

Why graphene?

- Need ballistic transport → high mobility and electron mean-free-path
- Graphene has high mobility at room temperature → no low T operation needed

# Introduction: objectives of simulations

- Find optimum geometry for the ballistic rectifier
- Estimate electrical parameters (output voltage, input resistance, responsivity)
- Study device behavior on suspended graphene (ballistic regime)
- Study device behavior on $SiO_2$ substrate (intrinsic phonons, remote phonons, edge defects)

# Model: Landauer-Buttiker

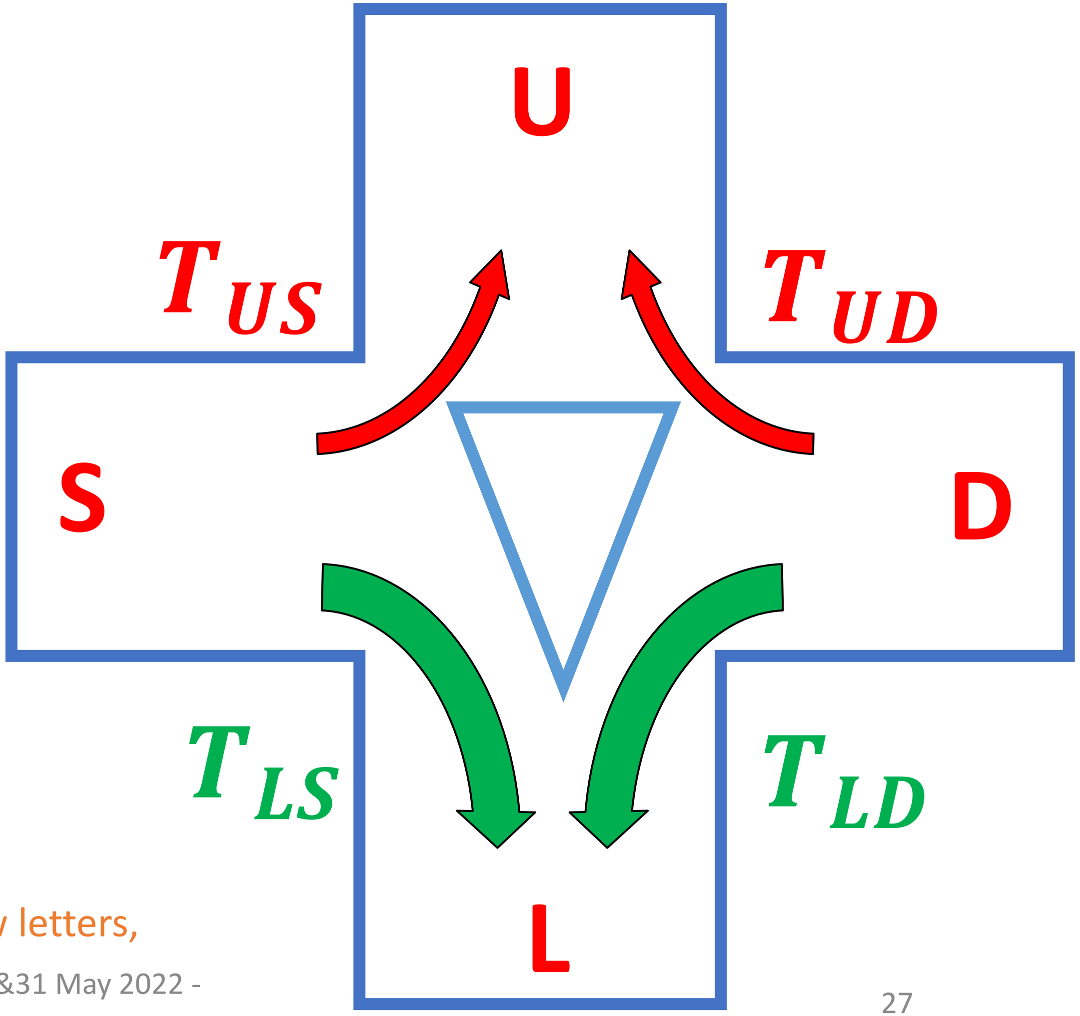
Synergistic use of Monte Carlo Simulation and Landauer-Buttiker formalism [2]

Imposing $I_L = I_U = 0$ we find

$$V_{LU} = \frac{G_{LS}(V_{SD})G_{UD}(V_{SD}) - G_{LD}(V_{SD})G_{US}(V_{SD})}{G_L S - \left(G_{SL}(V_{SD}) + G_{DL}(V_{SD})\right)\left(G_{LD}(V_{SD}) + G_{LS}(V_{SD})\right)} V_{SD}$$

$$= \frac{A(V_{SD})}{B(V_{SD})} V_{SD}$$

$$G_{ij}(V_{SD}) = \frac{2q^2 W k_b T}{\pi^2 v_f \hbar^2} T_{ij}(V_{SD}) log\left(1 + e^{E_f/k_b T}\right)$$




$T_{ij}$ is the transmission probability $0 \leq T_{ij} \leq 1$
where *j* is the injection and *i* the collection terminal

[2] Büttiker, M. (1986). Four-terminal phase-coherent conductance. Physical review letters, 57(14), 1761.

# Model: Landauer-Buttiker

In order to consider both electrons and holes transport

$$G_{ij}(n, V_{SD}) = G_{ij}{}^{e}(n, V_{SD}) + G_{ij}{}^{h}(p, V_{SD})$$

where $G_{ij}{}^{h}(p, V_{SD}) = G_{ij}{}^{e}(n_i{}^2/n, -V_{SD})$ with $n_i$ intrinsic carrier density

Evaluations performed considering $V_{SD}$ as DC Voltage

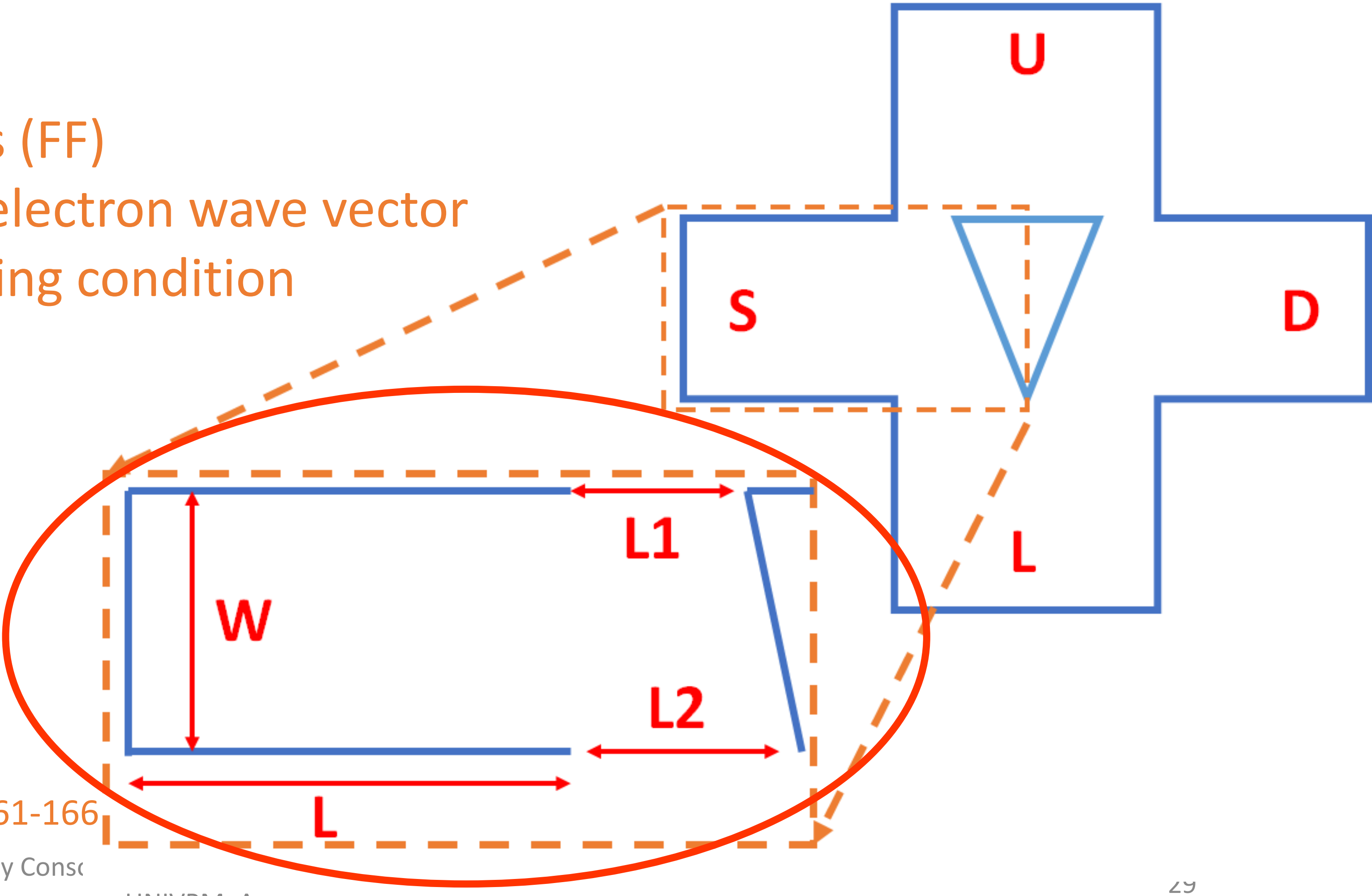
# Model: Monte Carlo simulation

$T_{ij}$ are calculated with MC simulator

MC technique [3]:

- Sequence of electron free-flights (FF)
- During FF electric field changes electron wave vector
- FF time is determined by scattering condition

Thanks to symmetry conditions we can restrict simulations to a sub-region of the overall device




[3] Bresciani M. et al. Solid-state electronics 89 (2013): 161-166

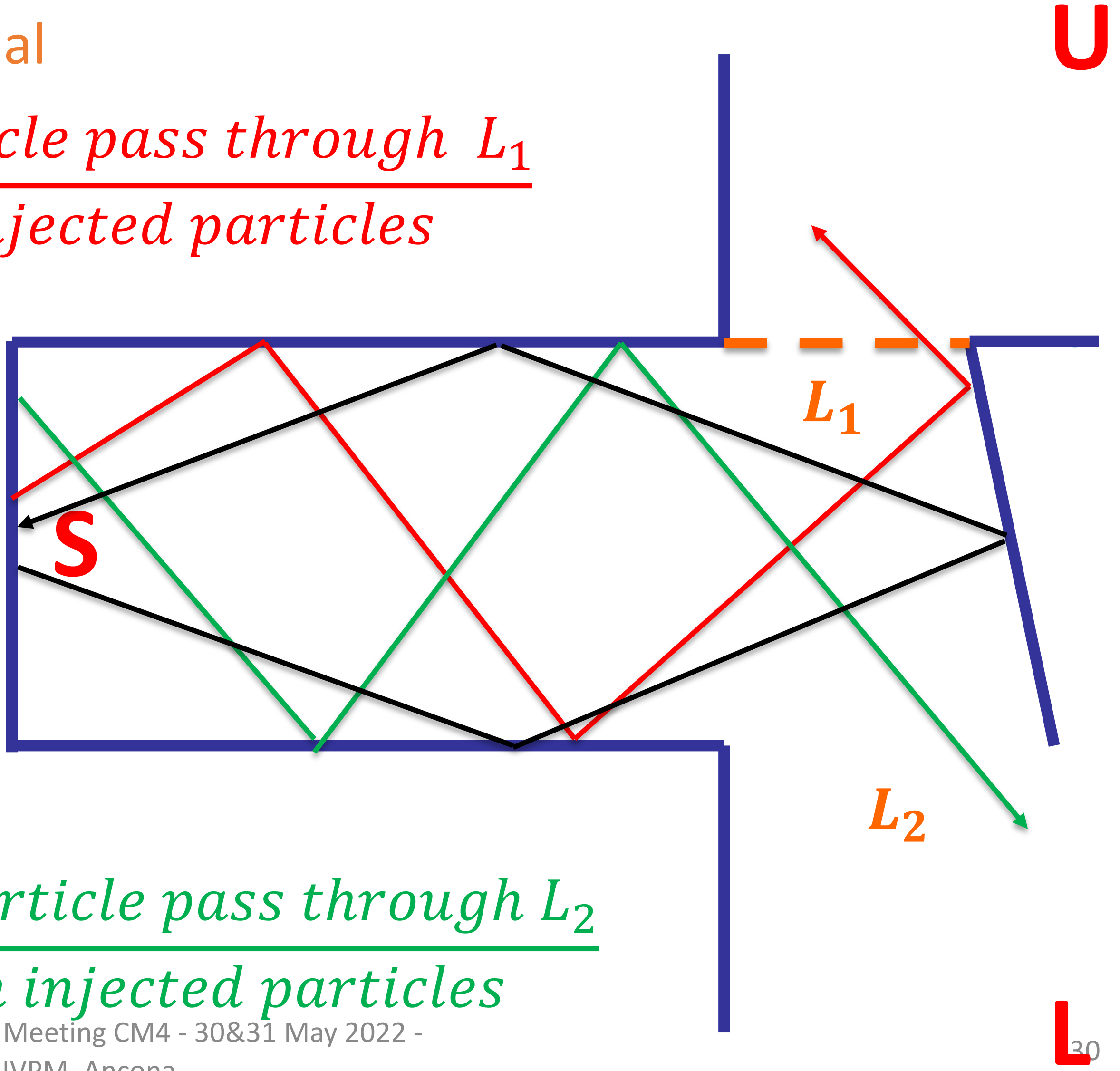
# Model: $T_{ij}$ calculation

- Particles injected randomly from S terminal

- Reflections:
  - Specularly
  - Random reflection (simulating edge defects)

$$T_{US} = \frac{n\ particle\ pass\ through\ \ L_1}{n\ injected\ particles}$$

$$T_{SS} = \frac{n\ particle\ come\ back\ S}{n\ injected\ particles}$$




$$T_{LS} = \frac{n\ particle\ pass\ through\ L_2}{n\ injected\ particles}$$

# Model: Symmetry

*S* and *D* terminals are totally equivalent and only $V_{SD}$ distinguishes the corresponding probabilities so we have

$$\begin{cases} \boldsymbol{T_{LS}(V_{SD}) = T_{LD}(V_{DS})} \\ \boldsymbol{T_{US}(V_{SD}) = T_{UD}(V_{DS})} \\ \boldsymbol{T_{DS}(V_{SD}) = T_{SD}(V_{DS})} \end{cases}$$

The remaining $T_{ij}$ with $j \neq \{S, D\}$ are assumed to fulfill the equilibrium condition

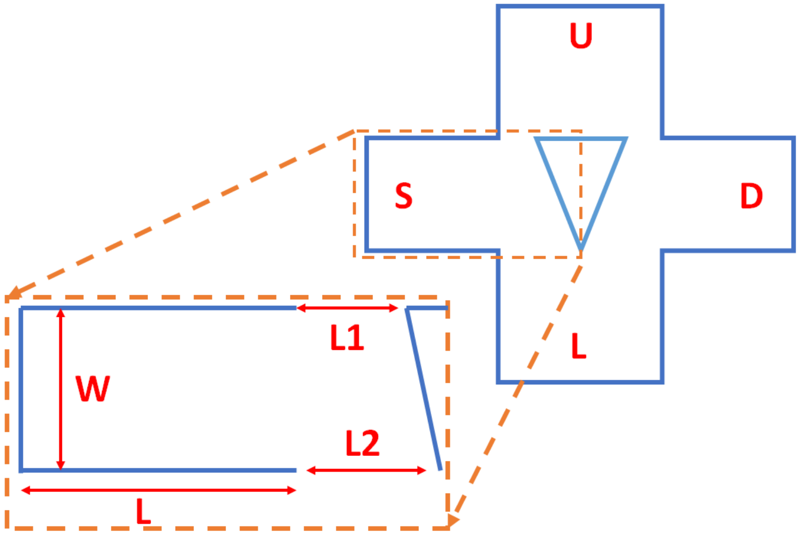
$$\boldsymbol{T_{ij} = T_{ji}}$$

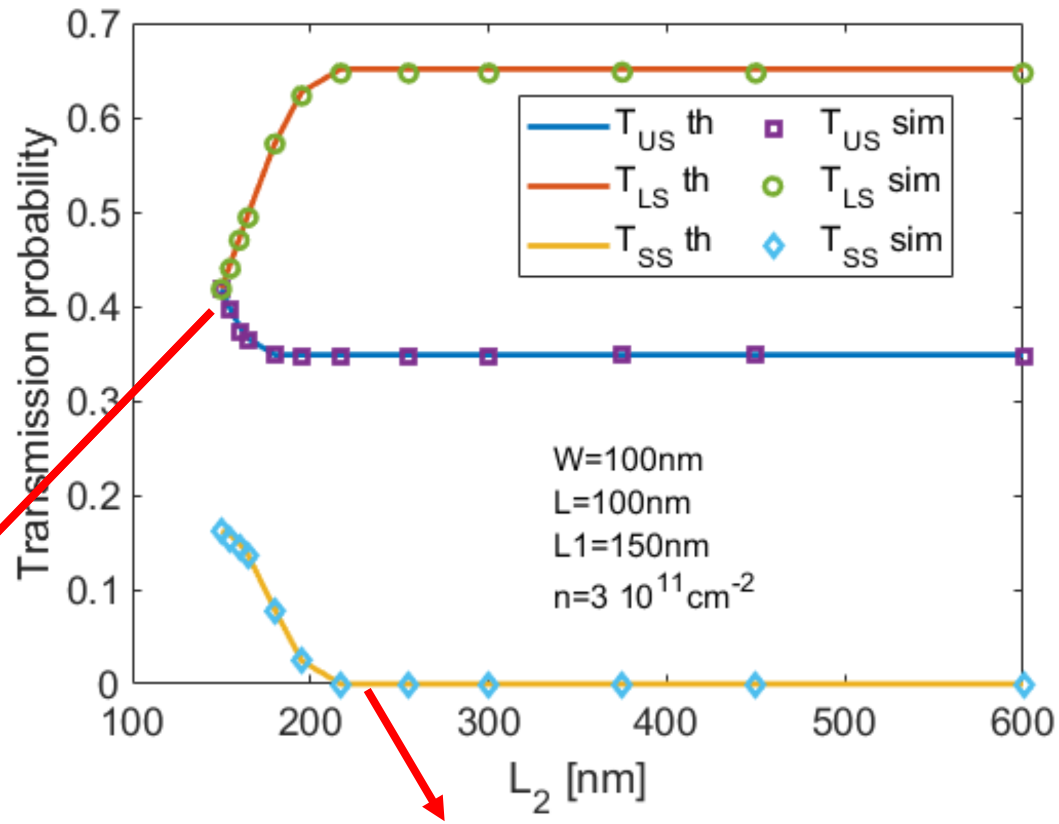
also when $V_{DS}$ is not zero. This approximation is valid for $I_L = I_U = 0$ [1]

[1] Song, A. M. (1999). Formalism of nonlinear transport in mesoscopic conductors. Physical review B, 59(15), 9806.

# Result: $T_{ij}$ comparison at E=0

- Comparison between $T_{ij}$ calculated with MC (sim) and analytical relation (th)
- $T_{ij}$ th : analytical expression can be obtained under ballistic transport and $V_{SD} = 0$
- Perfect agreement between results



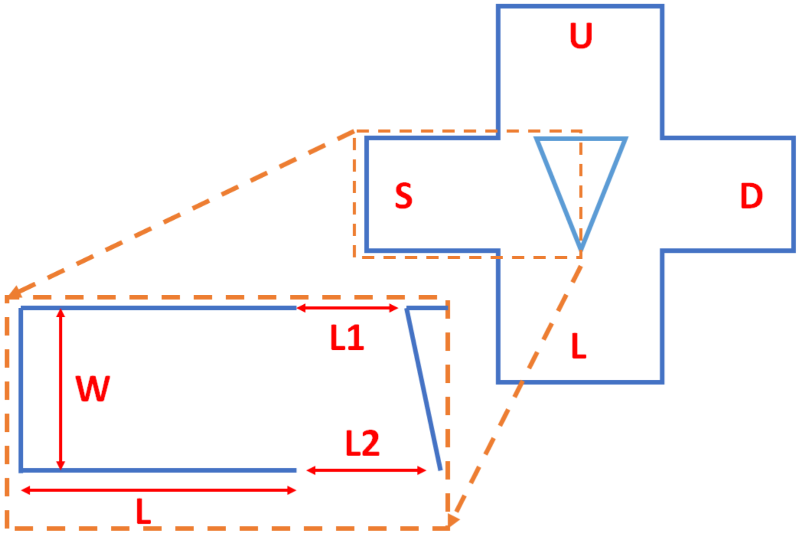

$T_{US} \rightarrow T_{LS}$ when $L_2 \rightarrow L_1$

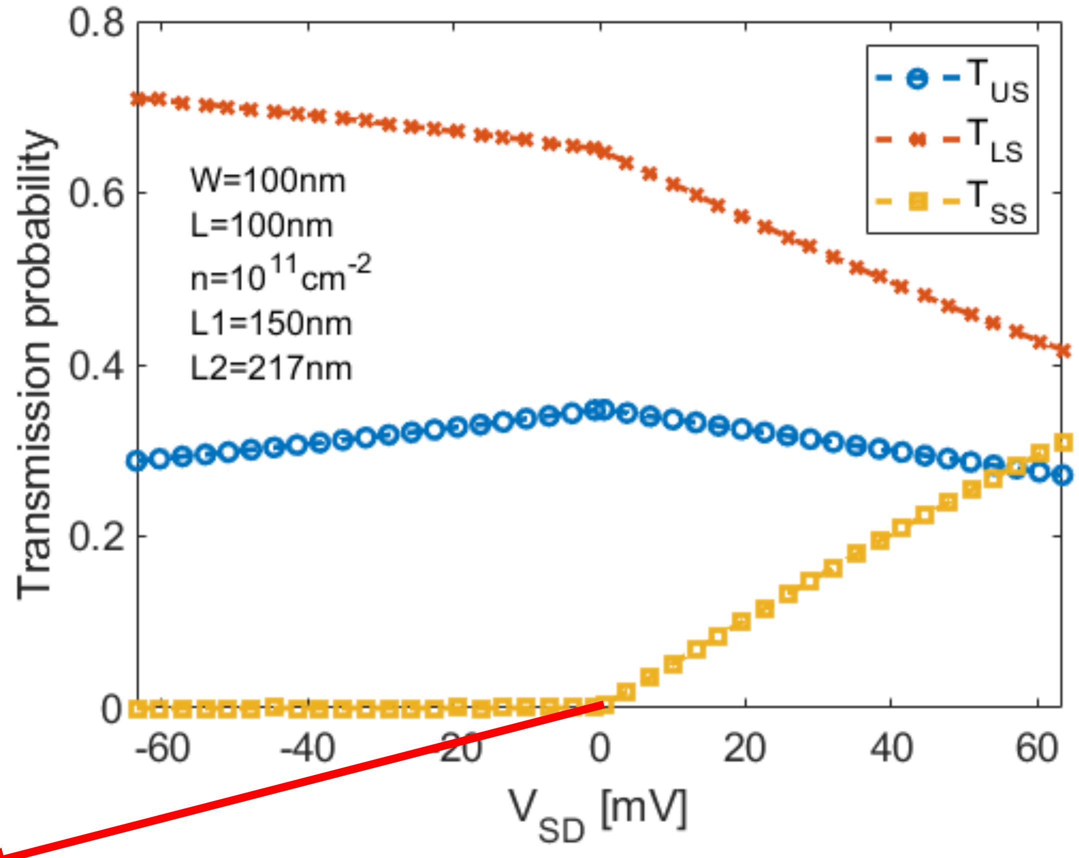
$T_{SS} = 0$ in ballistic regime if

$$L_2 > L_1\left(1 + \left(\frac{W}{L_1}\right)^2\right)$$

# Result: $T_{ij}$ vs $V_{SD}$

- If $V_{SD} \neq 0$ no simple analytical relation can be derived
- MC simulations provide $T_{ij}$ also for arbitrary transport conditions

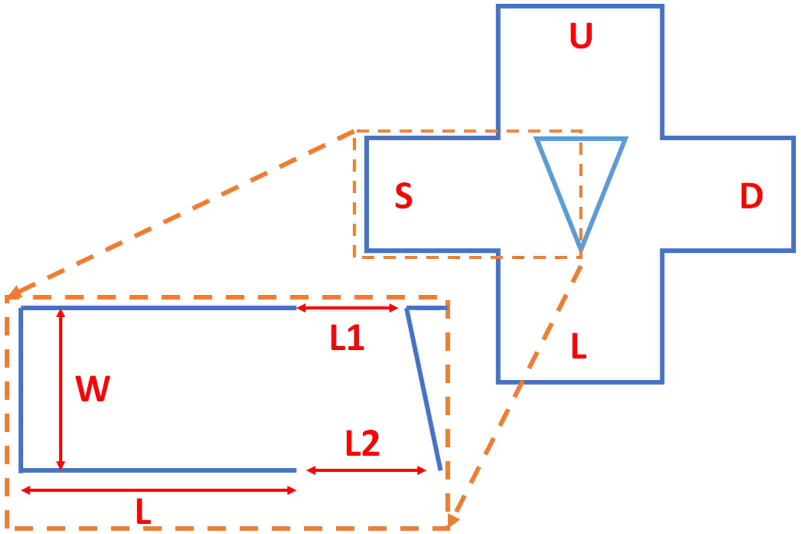


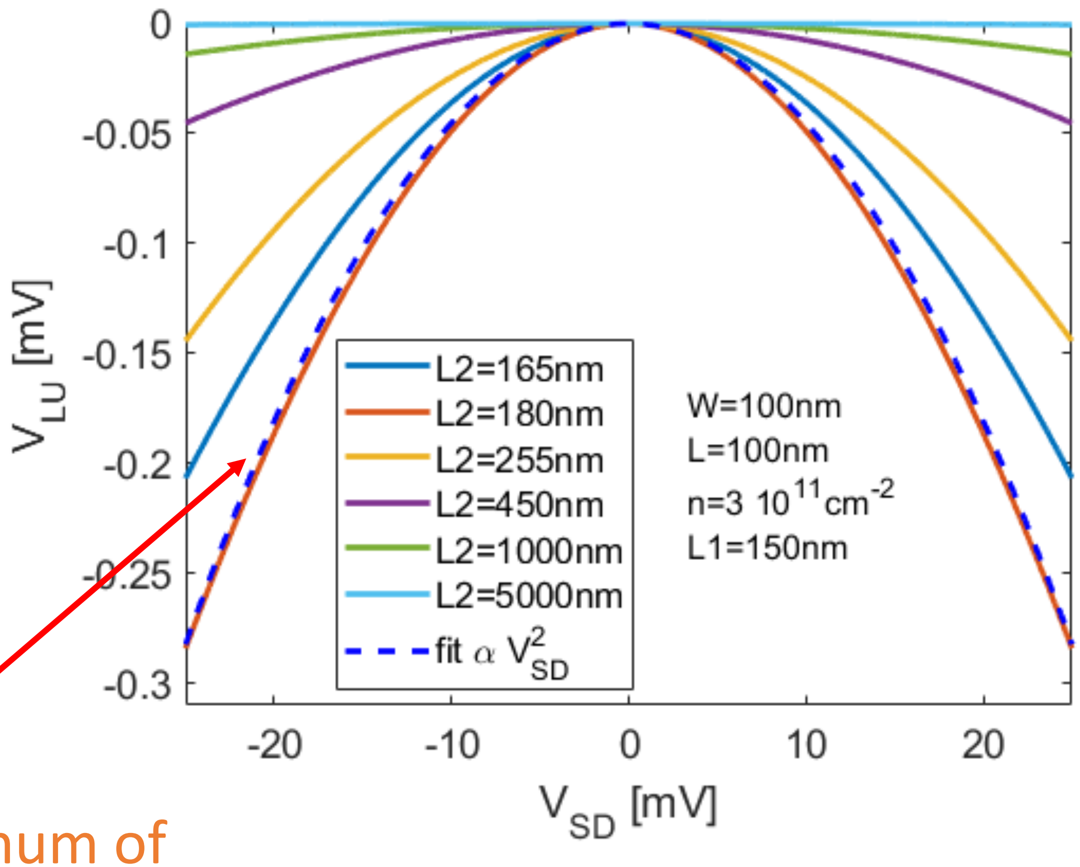




If $V_{SD} > 0$ $T_{SS}$ can be non null even if $L_2 > L_1\left(1 + \left(\frac{W}{L_1}\right)^2\right)$ is satisfied

# Result: $V_{LU}$ vs $V_{SD}$

- We observe a quadratic relationship between input and output voltage
  $$V_{LU} \approx \alpha V_{SD}{}^2$$
- $L_2 \rightarrow \infty$ $\quad\quad V_{LU} \rightarrow 0$



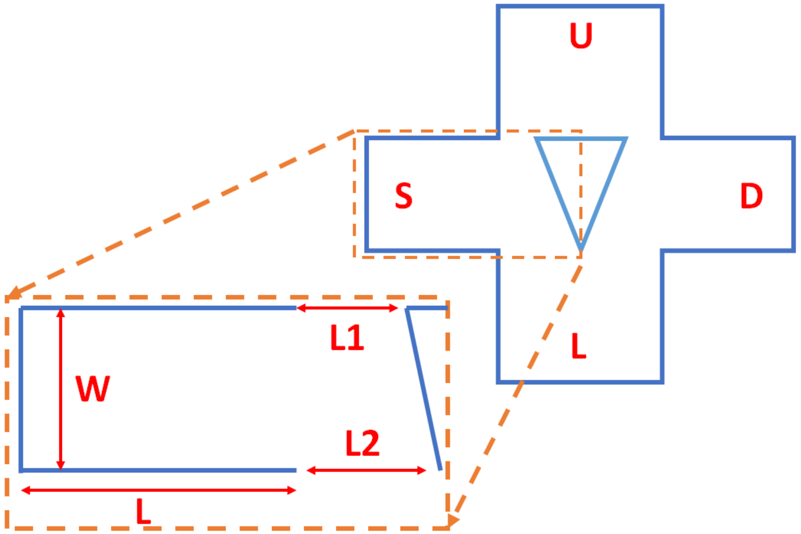

We find a maximum of $V_{LU}$ for $L_2 \approx 180nm$

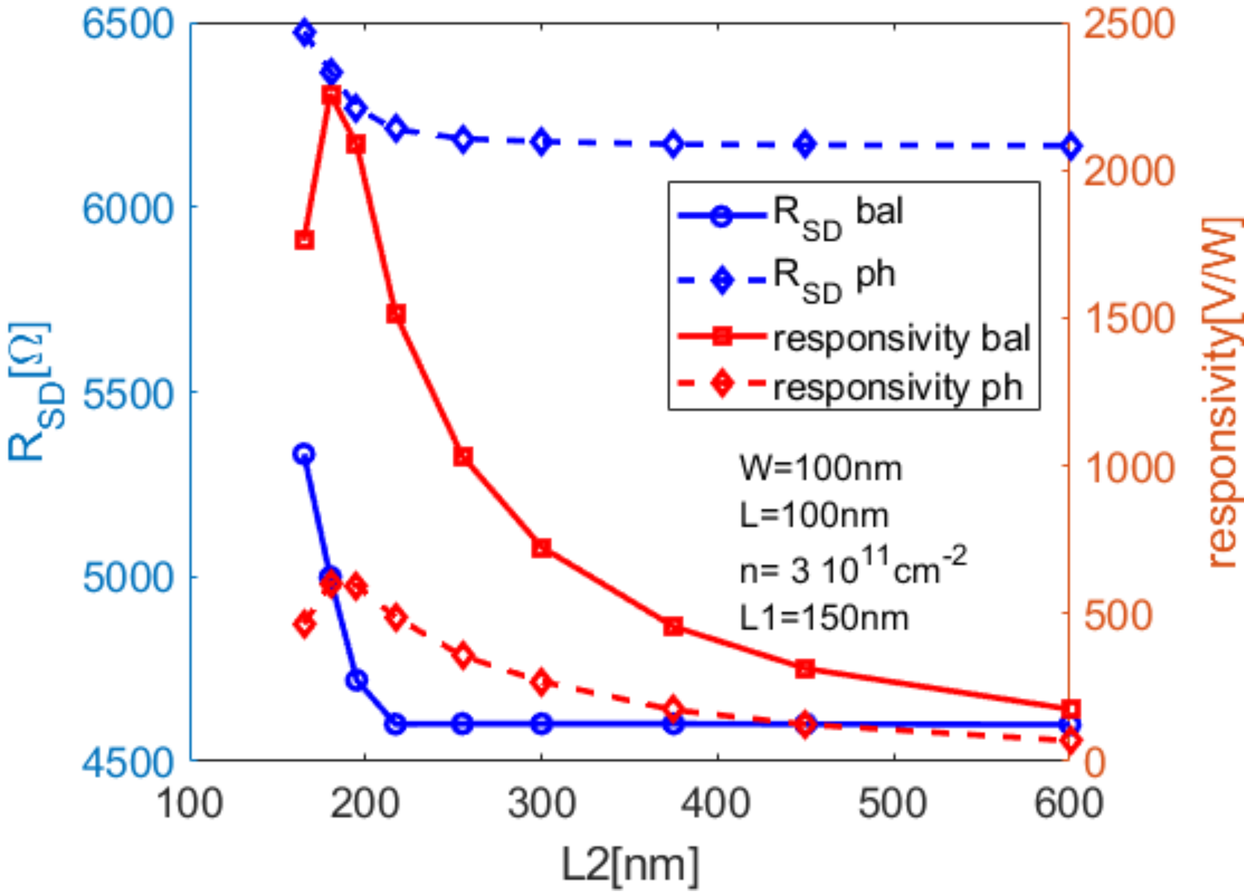
# Result: $r$ vs $L_2$

- We define responsivity

$$r = \frac{V_{LU}}{P_{in}} = \frac{\alpha {V_{SD}}^2/2}{{V_{SD}}^2/(2R_{SD})} = \alpha R_{SD}$$

- We find a maximum responsivity at $L_2 \approx 180nm$

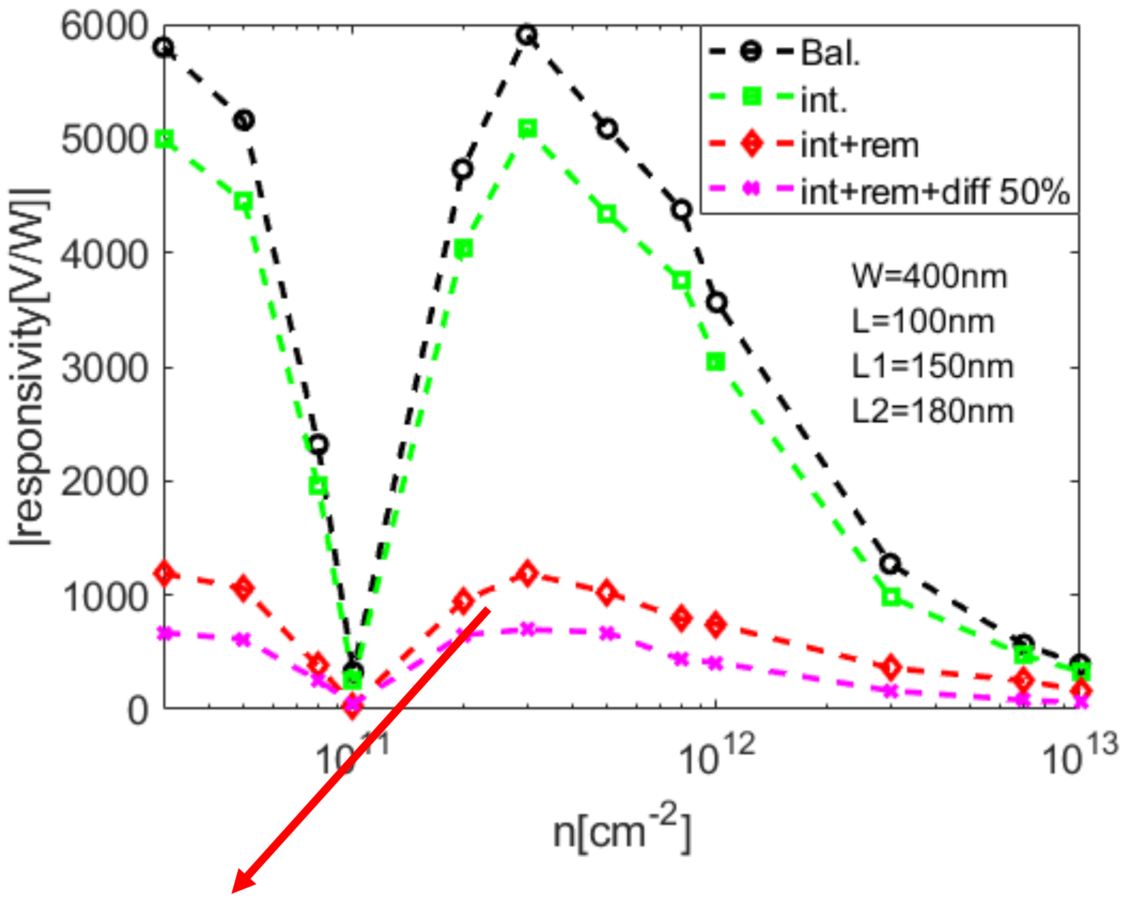


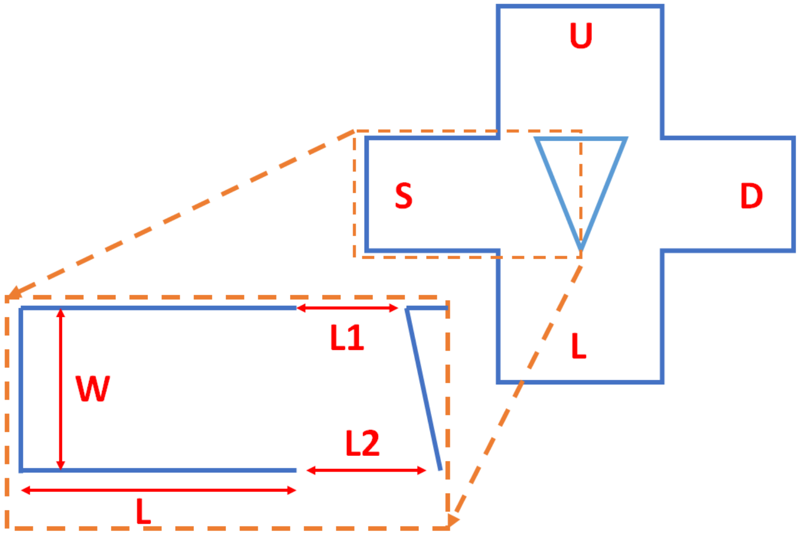




Responsivity is evaluated for $V_{SD} \to 0$

# Result: $r$ vs n

- Maximum responsivity at $n \approx 3\ 10^{11} cm^{-2}$
- High responsivity value also in scattering conditions
- Minimum responsivity at $n \approx 10^{11} cm^{-2}$ corresponding to Dirac point where $p = n$

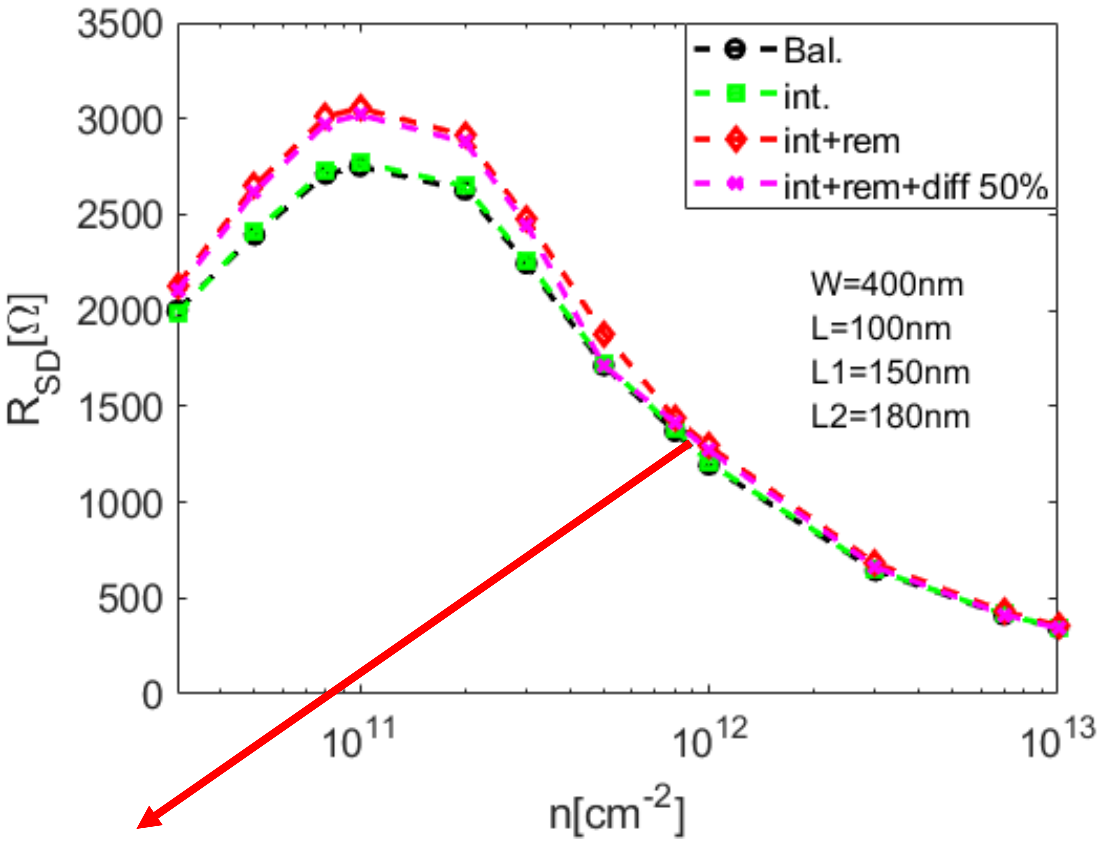


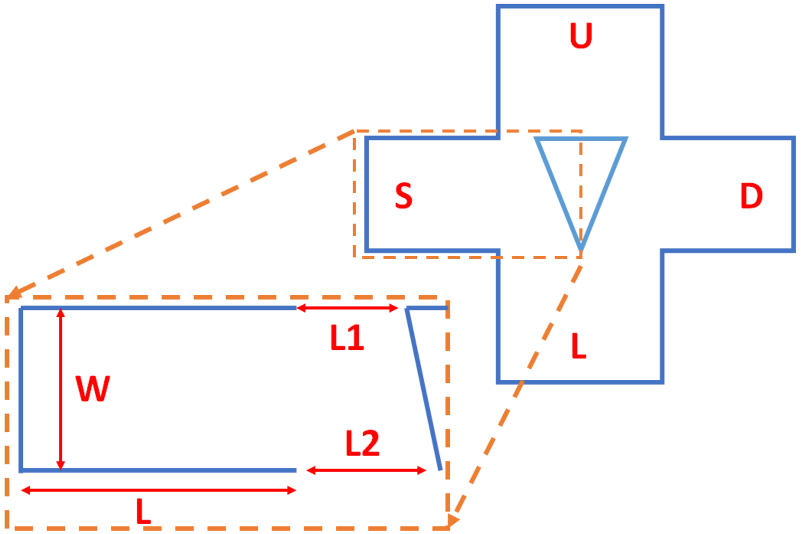




Strong impact of remote phonons on responsivity

# Result: $R_{SD}$ vs n

- Maximum $R_{SD}$ at Dirac point $n \approx 10^{11} cm^{-2}$
- $R_{SD}$ degrades when the Fermi level enters the conduction band and the electron concentratio increases

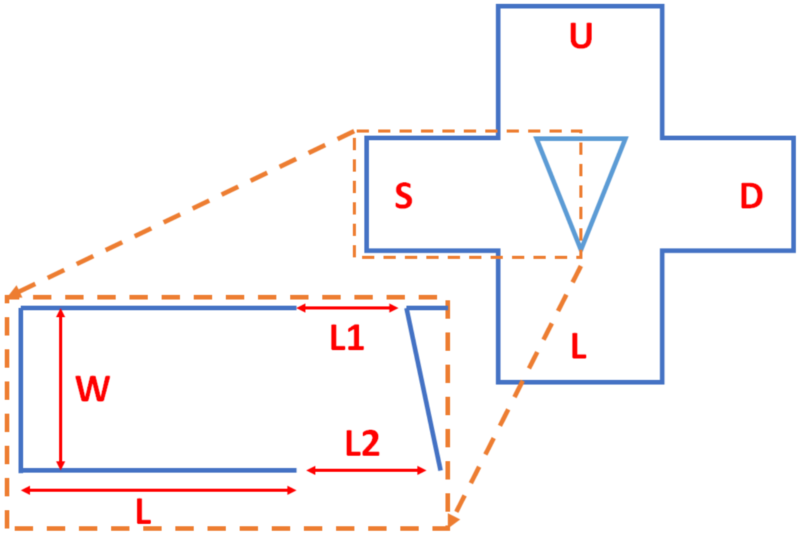


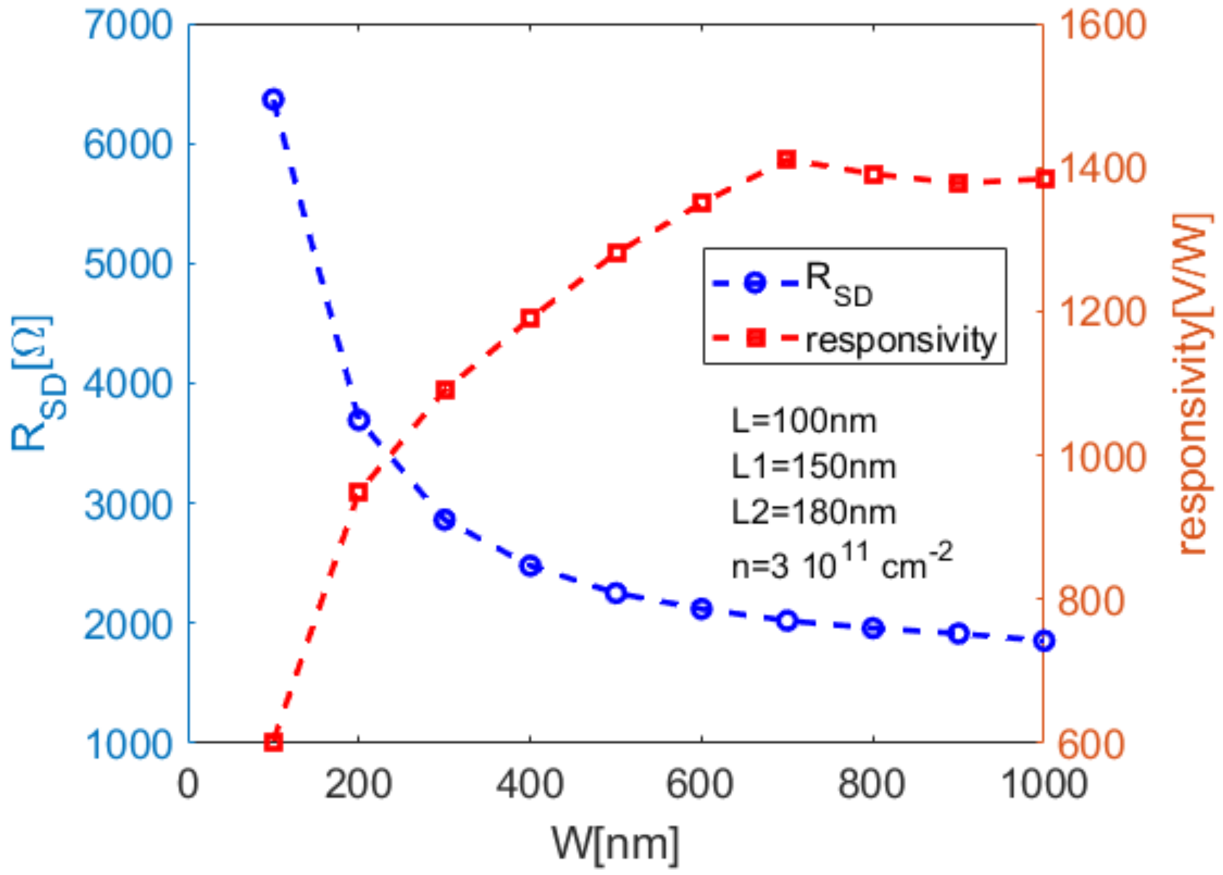




$n > 10^{12} cm^{-2}$
Same behavior regardless transport conditions

# Result: $r$ vs W

- Responsivity increases for W up to 700nm
- $R_{SD}$ decreases with W




Simulation with Intrinsic and remote phonons activated

# Conclusion

- Simulations have shown high responsivity values for:
  - $n \approx 3\, 10^{11}\, cm^{-2}$
  - $L_1 = 150\, nm \quad L_2 = 180\, nm$
  - $W = 700\, nm$

- Strong impact of remote phonons on responsivity

- Future goals: full structure simulation coupled with electrostatic
  - Device frequency dependence
  - Dependence on external loads ($I_L \neq 0$ *and* $I_U \neq 0$ )
  - Comparison with previous results

Thank you for your attention

More information is available at **www.greenergy-project.eu**

GreEnergy

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