croma
Centre for Radiofrequencies, Optics and Micro-nanoelectronics in the Alps

Greener RF vs RF for sustainability

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Grenoble, 19/06/2025

2.2W, class A

6.99€

50 000 H

VS

4.9W, class F

1.49€

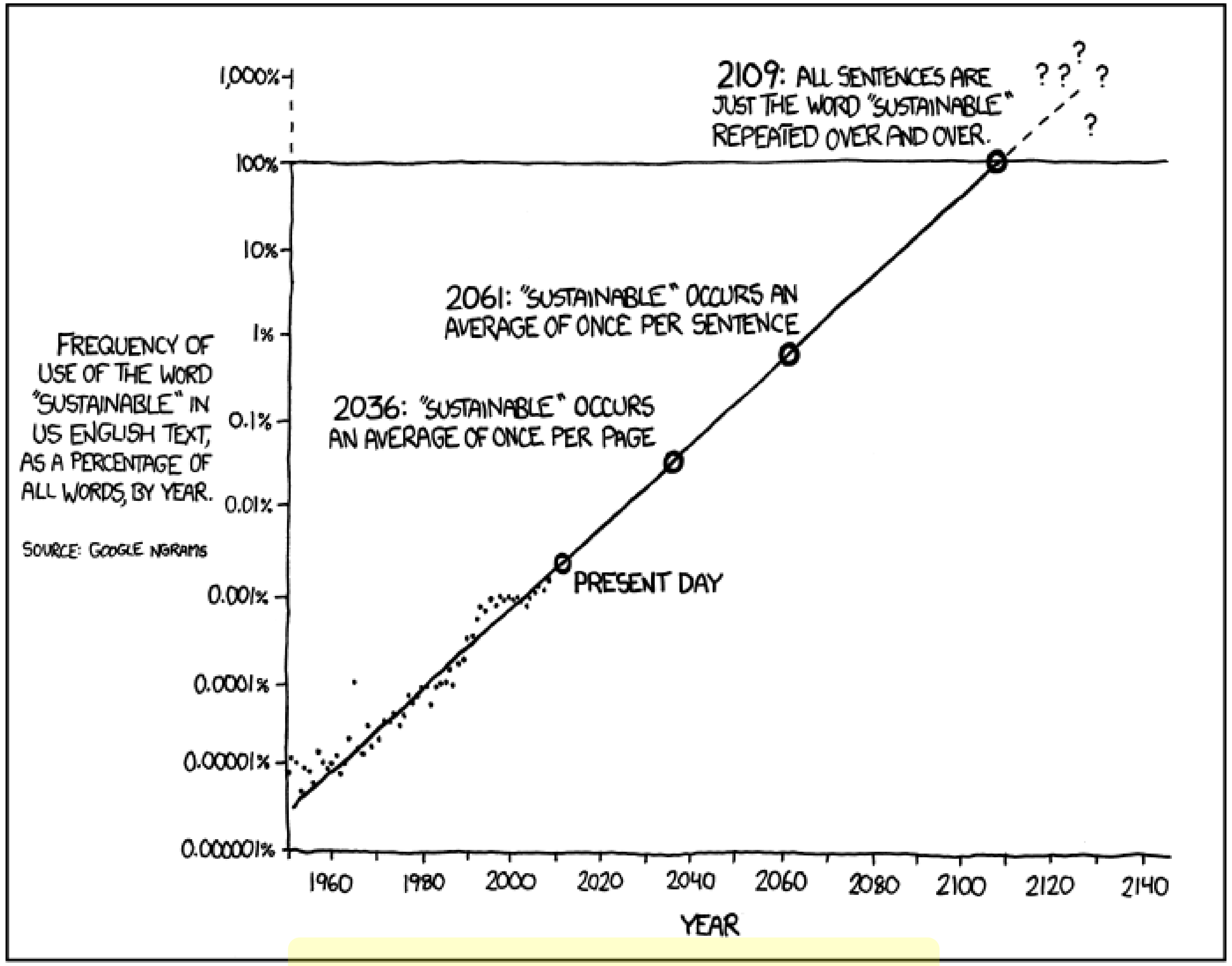
15 000 H

Abstract

- Overview on some **possibilities and challenges** for greener RF
- Discussion on the compromise between environment / performance

Abstract

- What is sustainability
- How Radio Frequency (RF) helps to achieve sustainability
- How to make RF greener



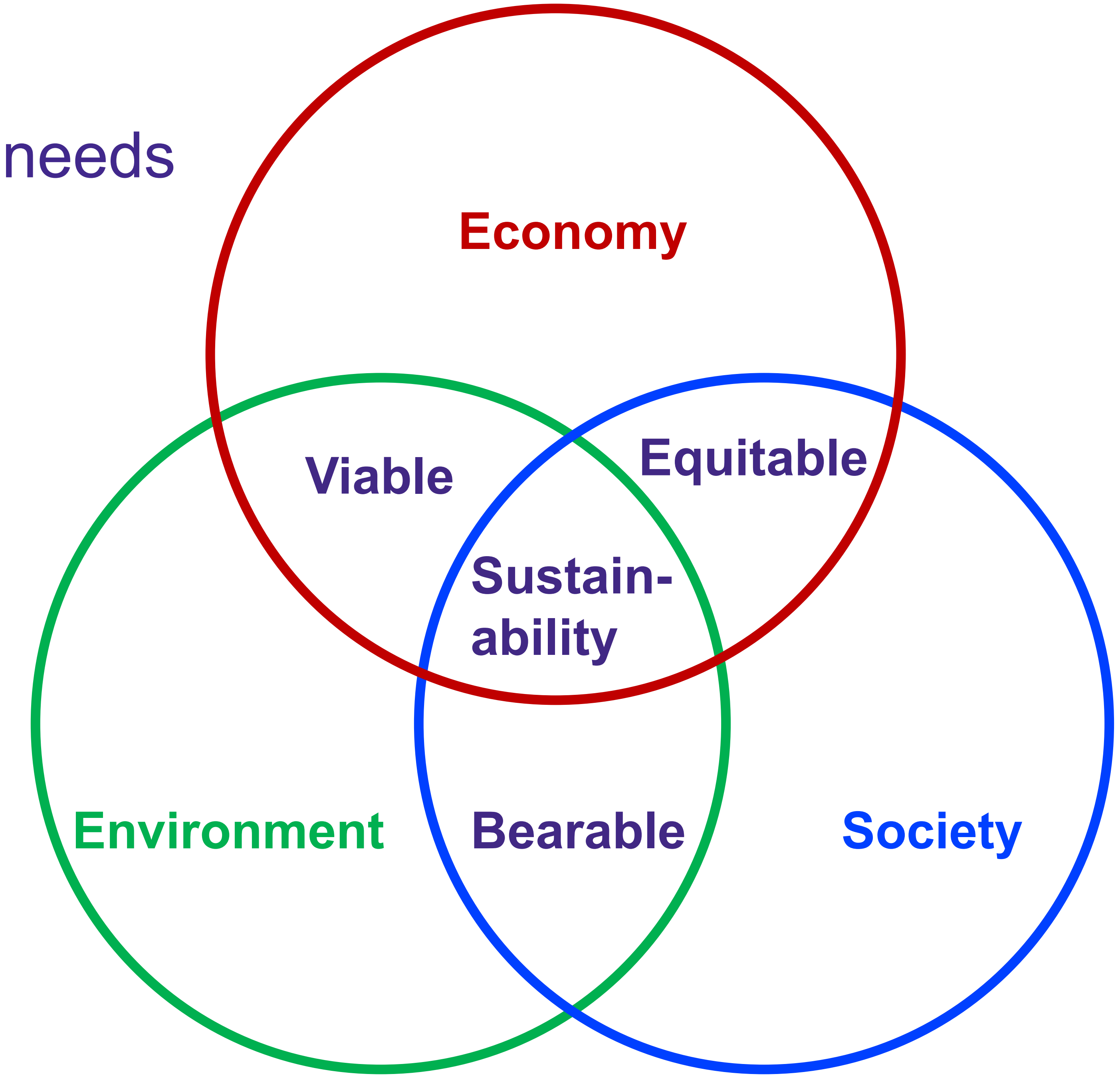
THE WORD "SUSTAINABLE" IS UNSUSTAINABLE.

https://xkcd.com/1007/

Definition of sustainability

Brundtland Report, 1987: "meeting the **needs** of the present **without compromising** the ability of future generations to meet their own needs"

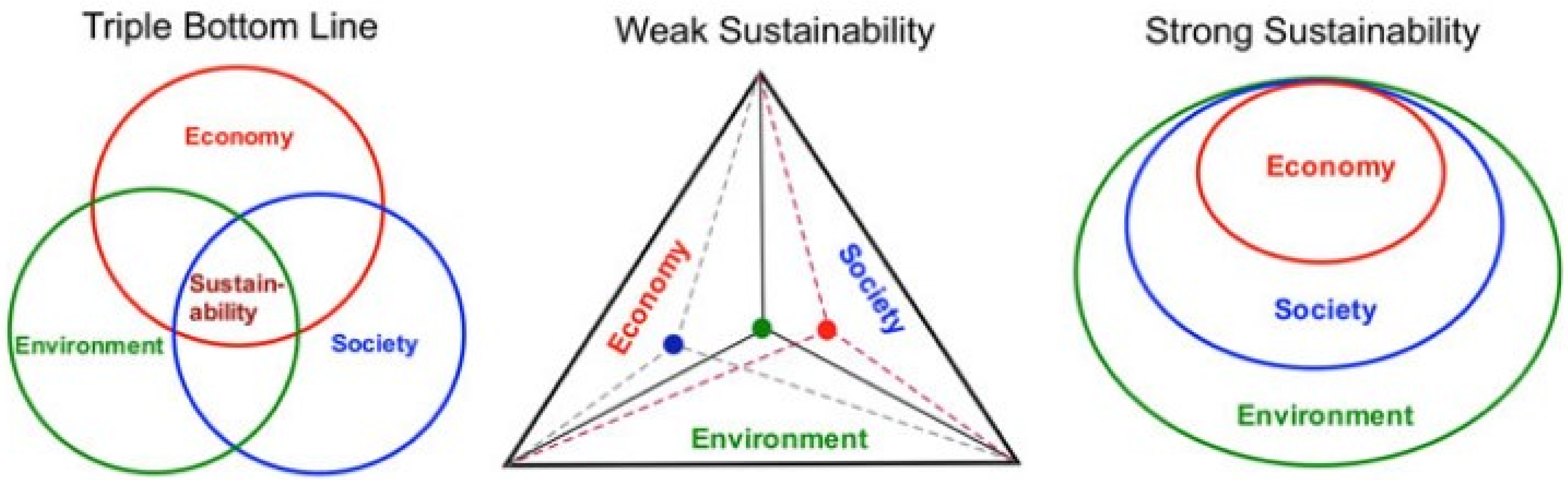
- Society: Needs of the present
- Environment: Ability of future generations to meet their own needs
- Economy: Method through which needs are met



J. Wu, Landscape Ecology, 2013

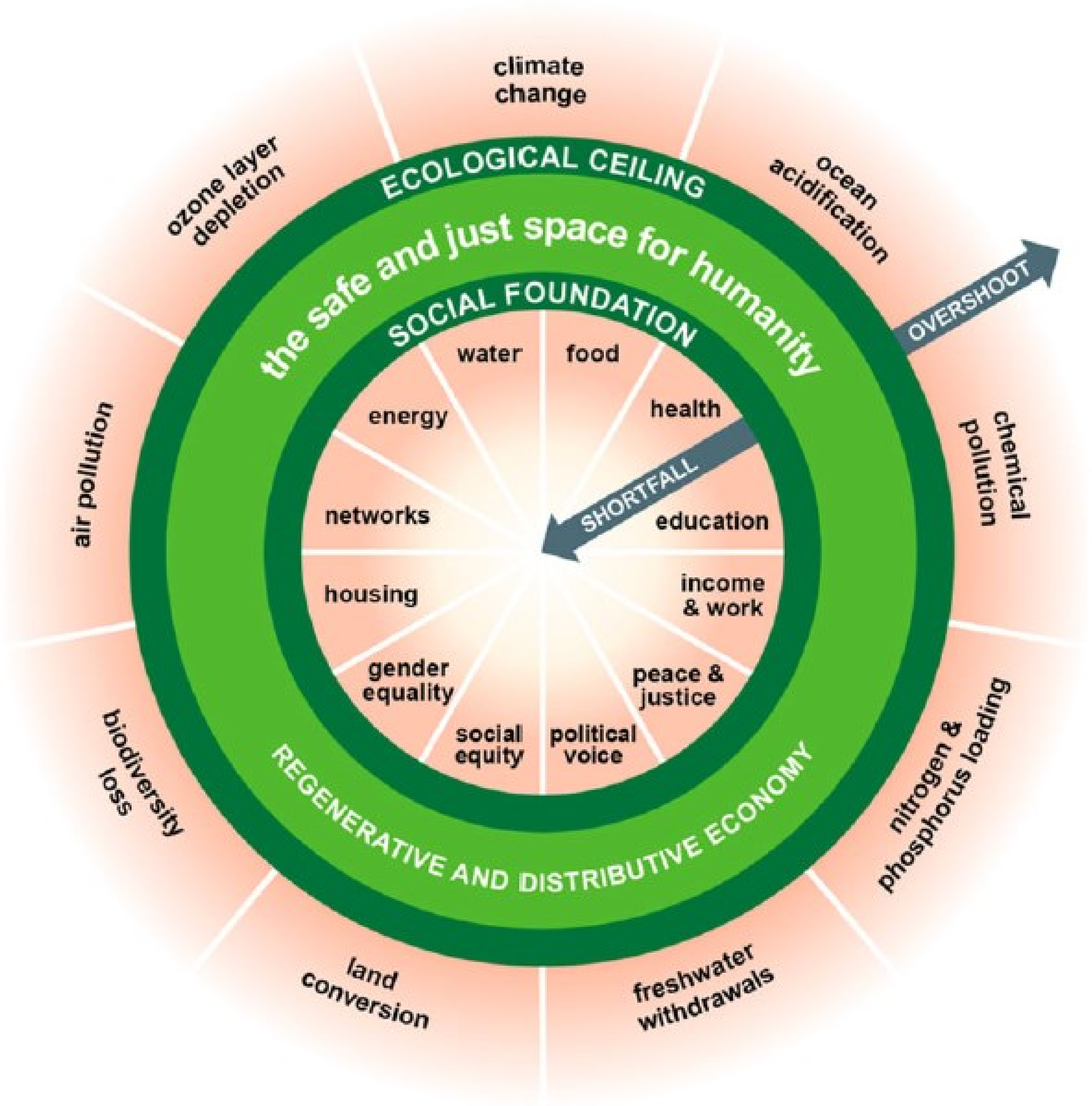
Some models to achieve sustainability

Brundtland Report, 1987: "meeting the **needs** of the present **without compromising** the ability of future generations to meet their own needs"



J. Wu, Landscape Ecology, 2013

Some models to achieve sustainability



K. Raworth, 2017

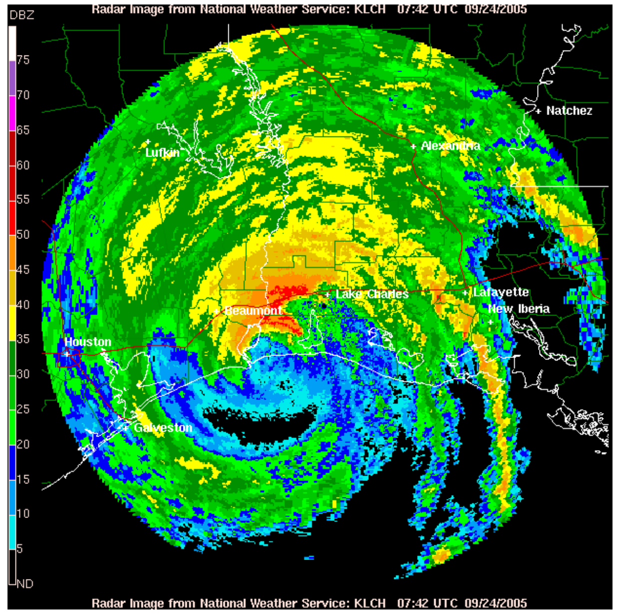
Abstract

- What is sustainability
- How Radio Frequency (RF) helps to achieve sustainability
- How to make RF greener

Radio Frequency (RF) in our life

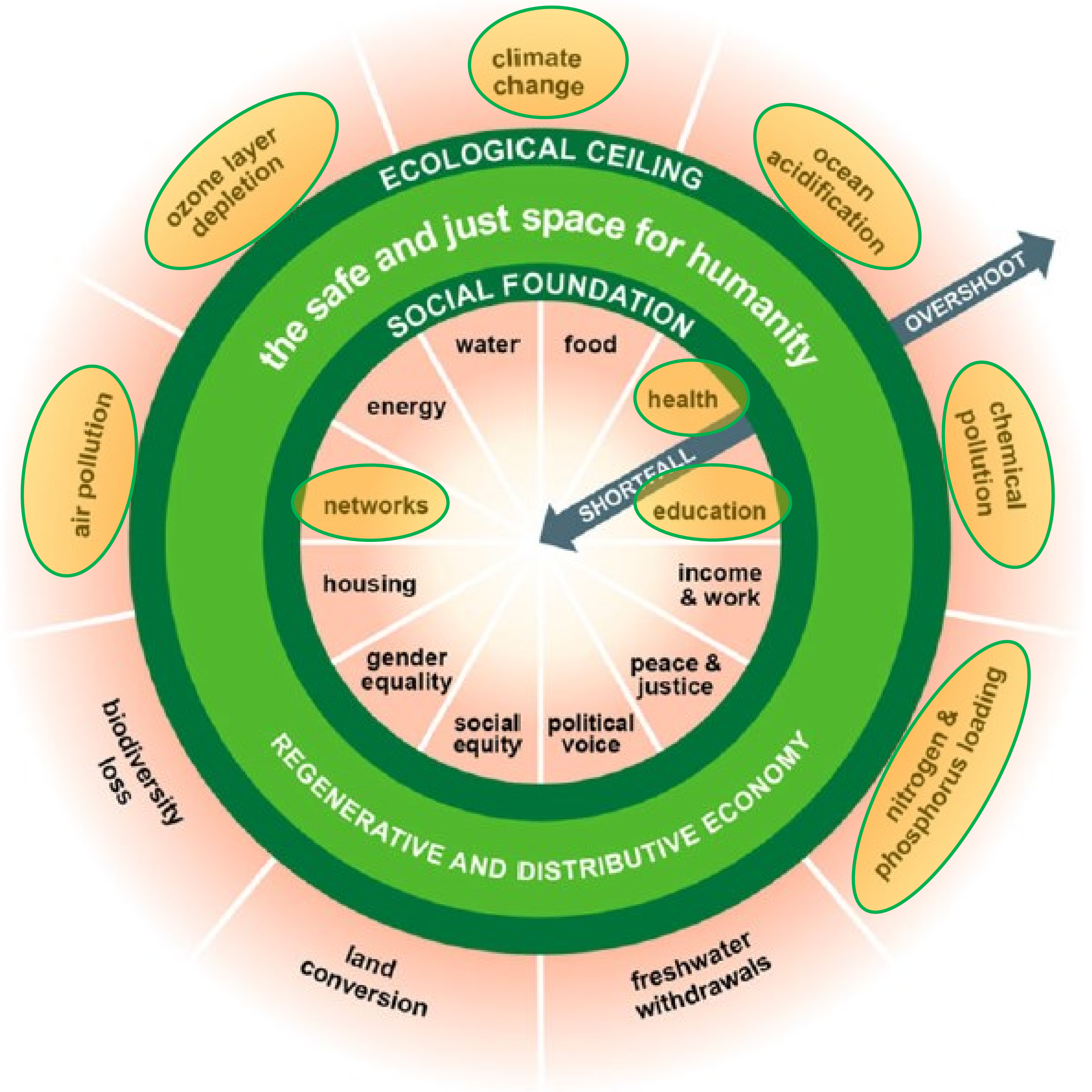
Communication

Radar



Weather monitoring

Heath monitoring
Air quality monitoring

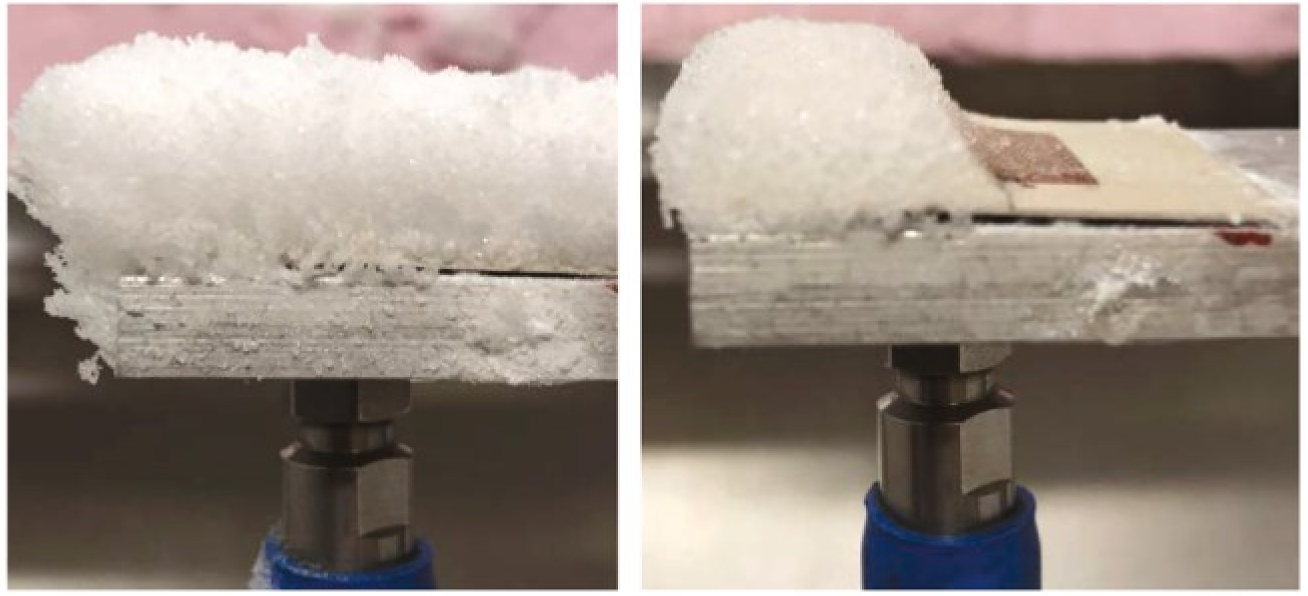


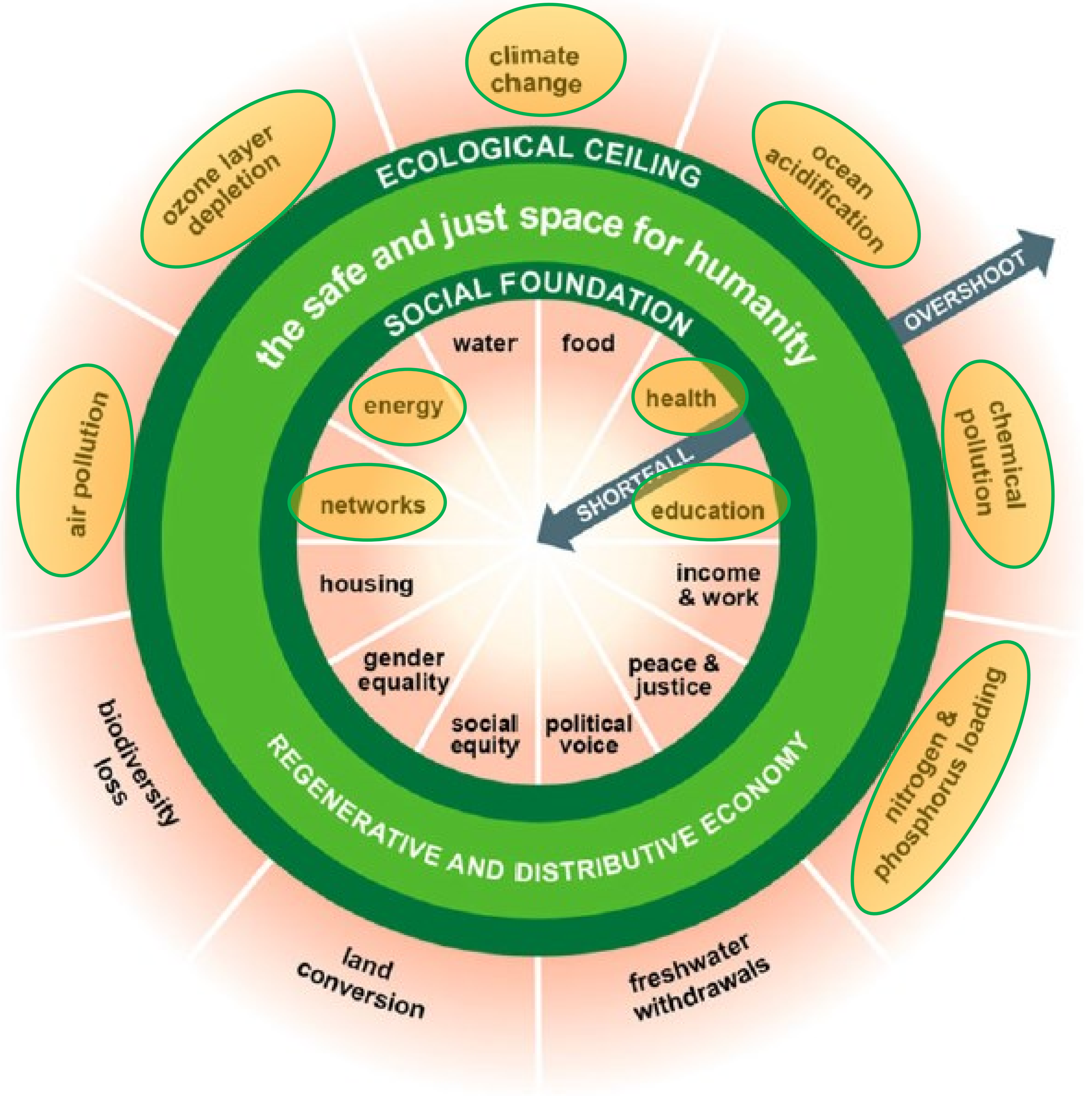
RF sensing – example on ice sensor

Ice formation reduces output performance

- ✓ reduce ~30% wind turbine output energy*
- ✓ Helicopter, aircraft
- ✓ …

*K. Wei *et al.*, Wind Energy, 2020

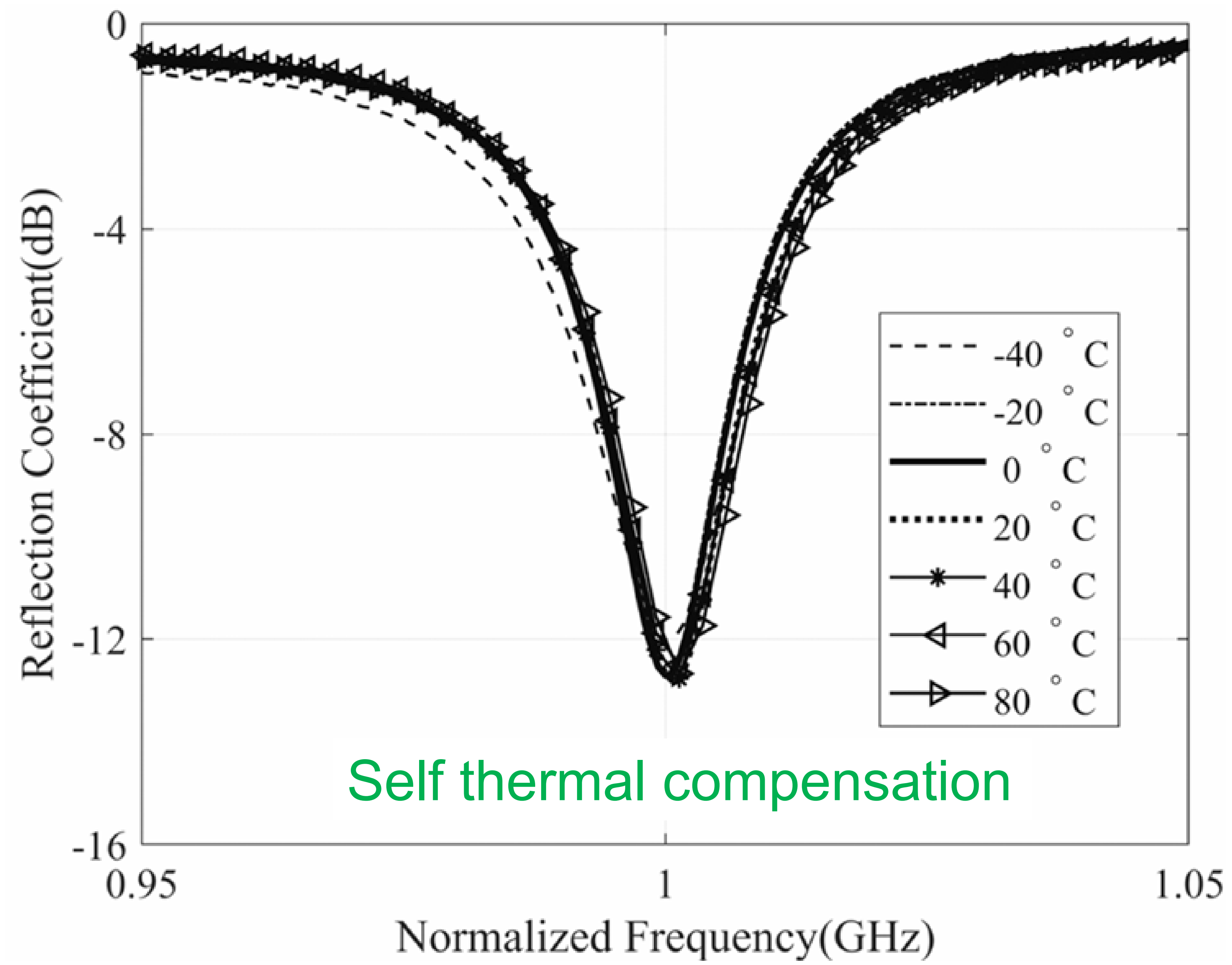


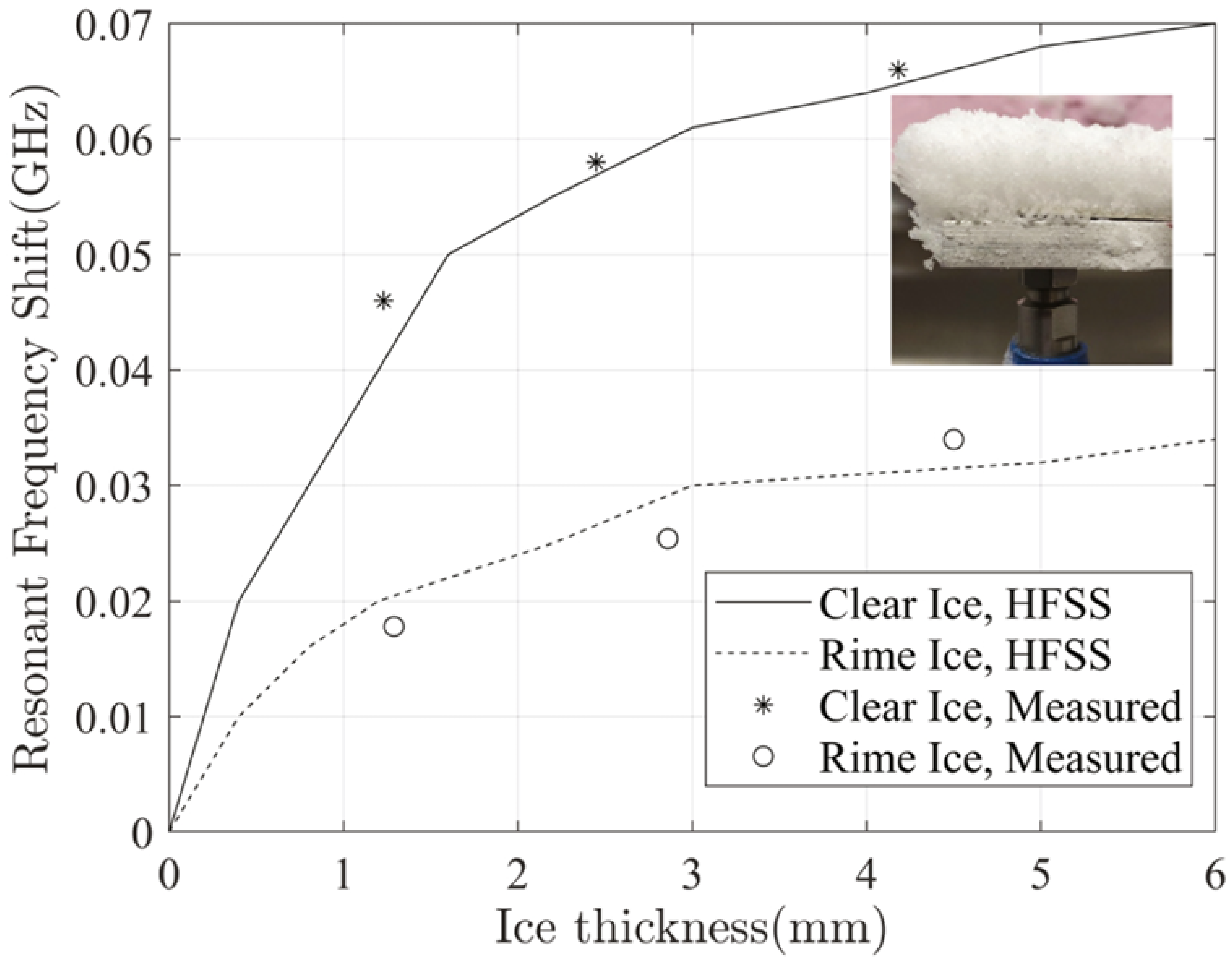


C. Li *et al.*, Sensors & Actuators: A. Physical, 2022

RF sensing – example on ice sensor

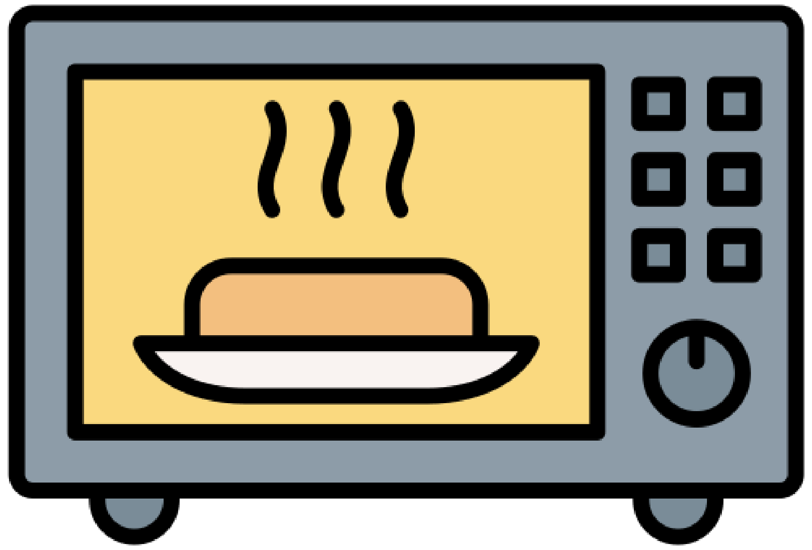
Can be customized to be sensible only to the interested parameters (ice thickness not temperature)





C. Li *et al.*, Sensors & Actuators: A. Physical, 2022

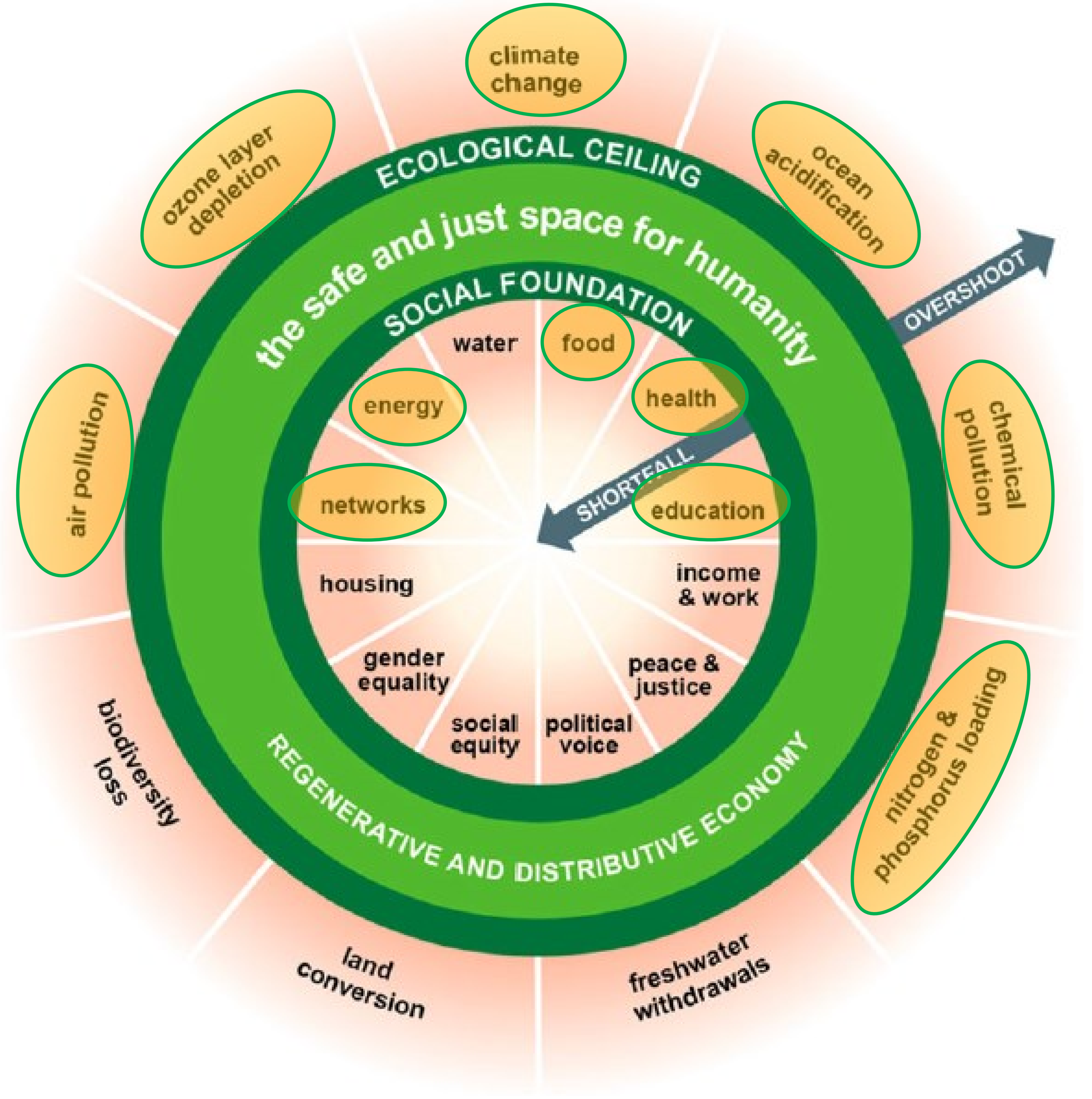
Radio Frequency (RF) in our life



Oven

Food drying

Microwave assisted heating improves the efficiency by 95% over the hot air alone*

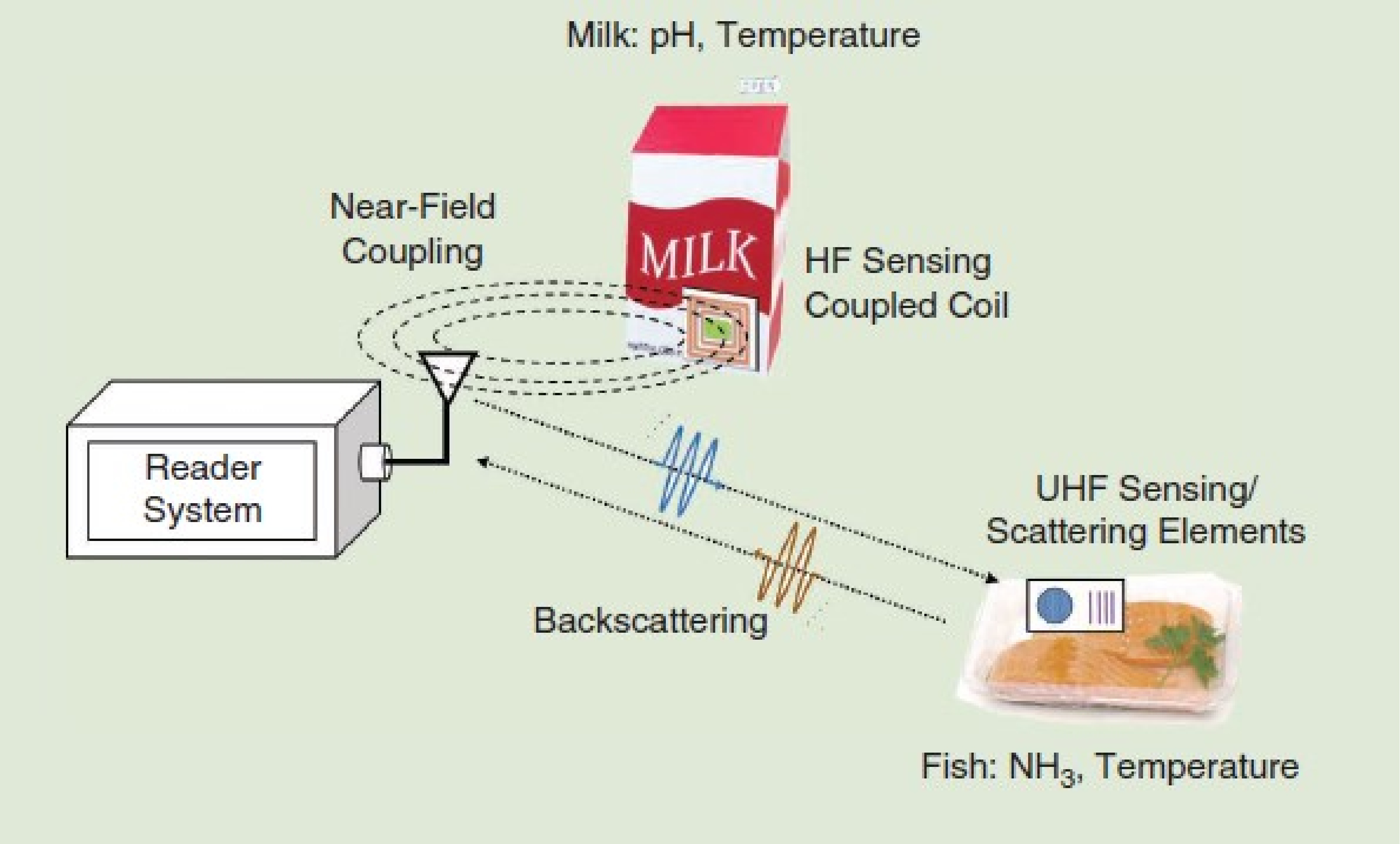


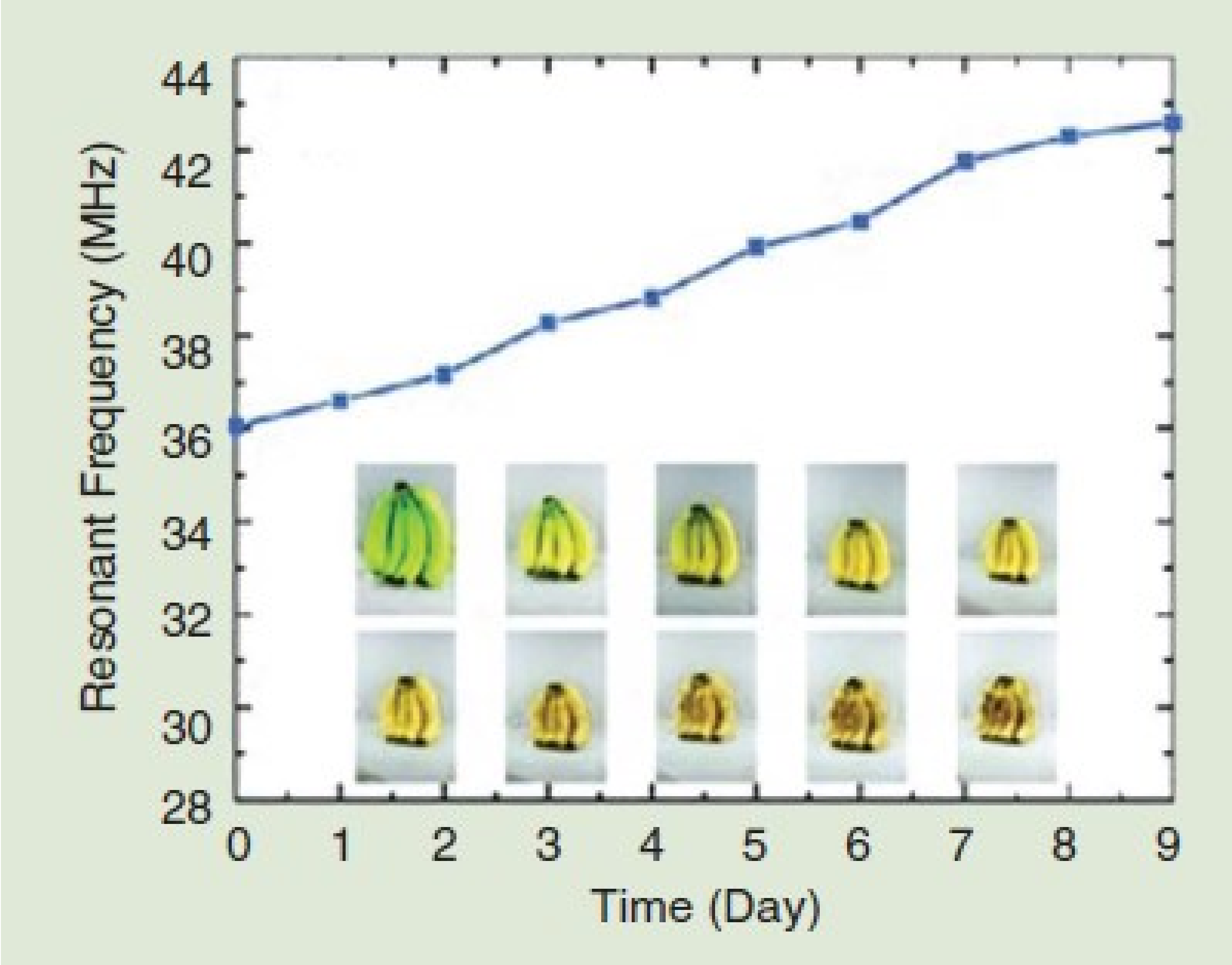
* R.S. Siegel and P. H. Siegel, IEEE Journal of microwave, 2023

RF for food quality monitoring

About 1/3 of food products are wasted!!!

Best before vs Expiry date





Food quality monitoring

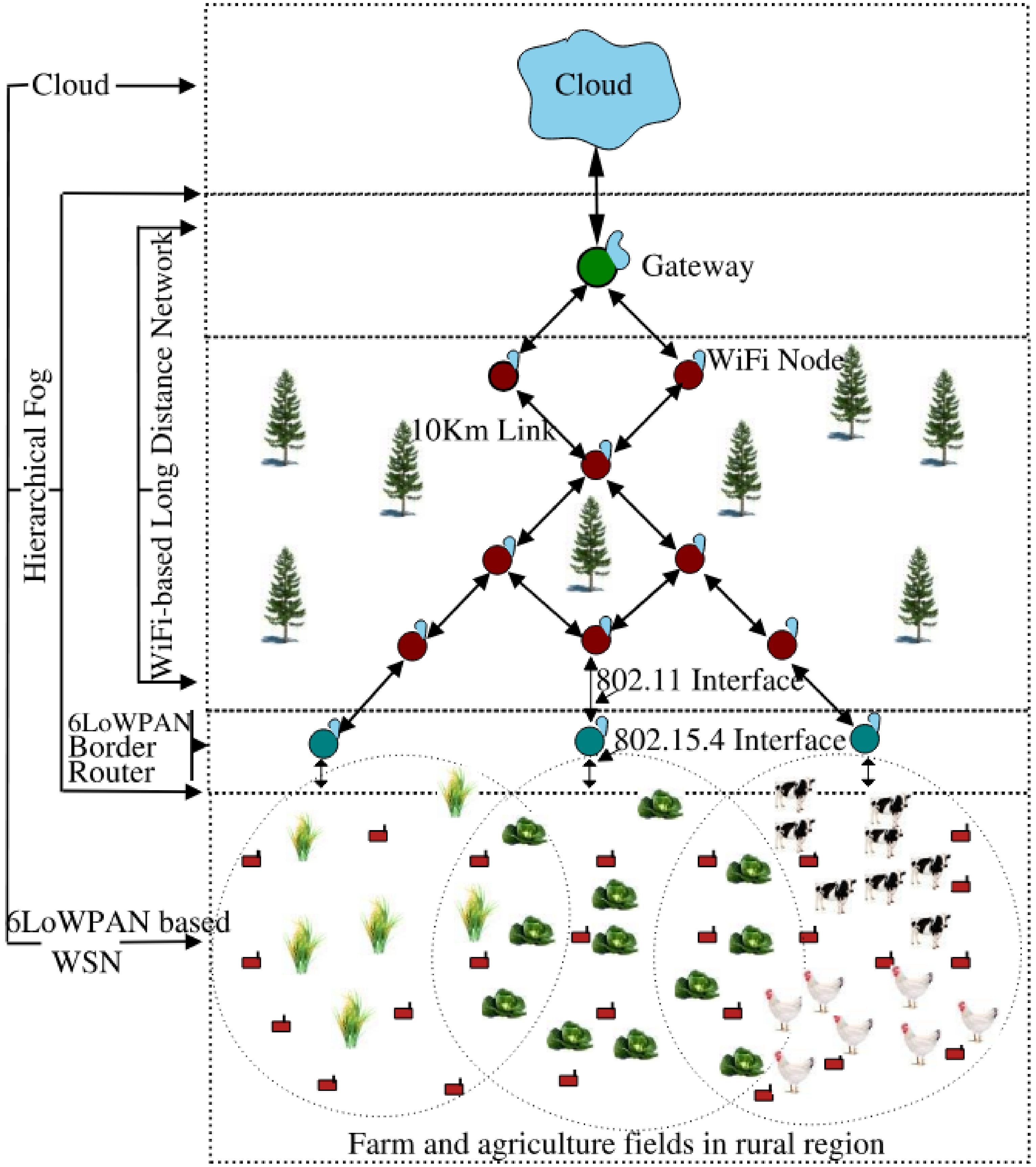
R, Raju *et al.*, IEEE Antenna and Propagation Magazine, 2020

RF for smart / precision agriculture

FAOSTAT in 2022:
Agriculture generates 16.2 Gt CO2eq (~30% of total GHG)

Wireless sensor network for precision agriculture
- Farm monitoring
- Irrigation
- Soil monitoring
- Water quality monitoring
- …

By 2050: IoT help to increase by 70% of food production in agriculture



N. Ahmed *et al.*, IEEE IoT Journal, 2018

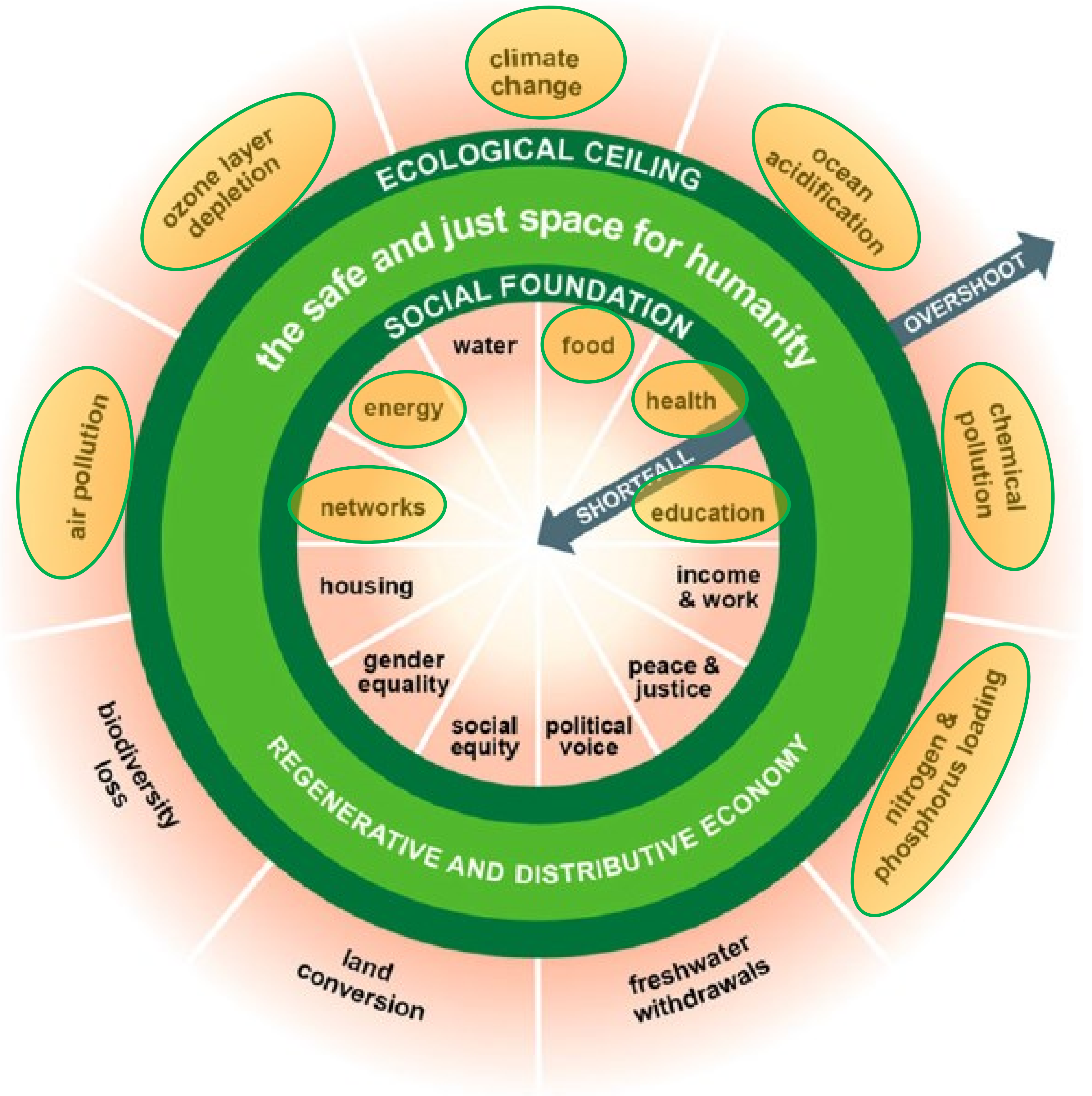
RF/antenna based sensors

Advantages of RF/antenna based sensors

- ❑ Wireless
- ❑ Can work without ADC/DAC
- ❑ Can “see through”
- ❑ Non invasive

Challenges of RF/antenna based sensors

- ❑ Sensitivity vs sensing range
- ❑ Variation with environment (other than sensing target)



And many other RF sensors

Abstract

- What is sustainability
- How Radio Frequency (RF) helps to achieve sustainability
- How to make RF greener

RF is essential in our life as well as for the future!

How to quantify if our solution is “greener" ?

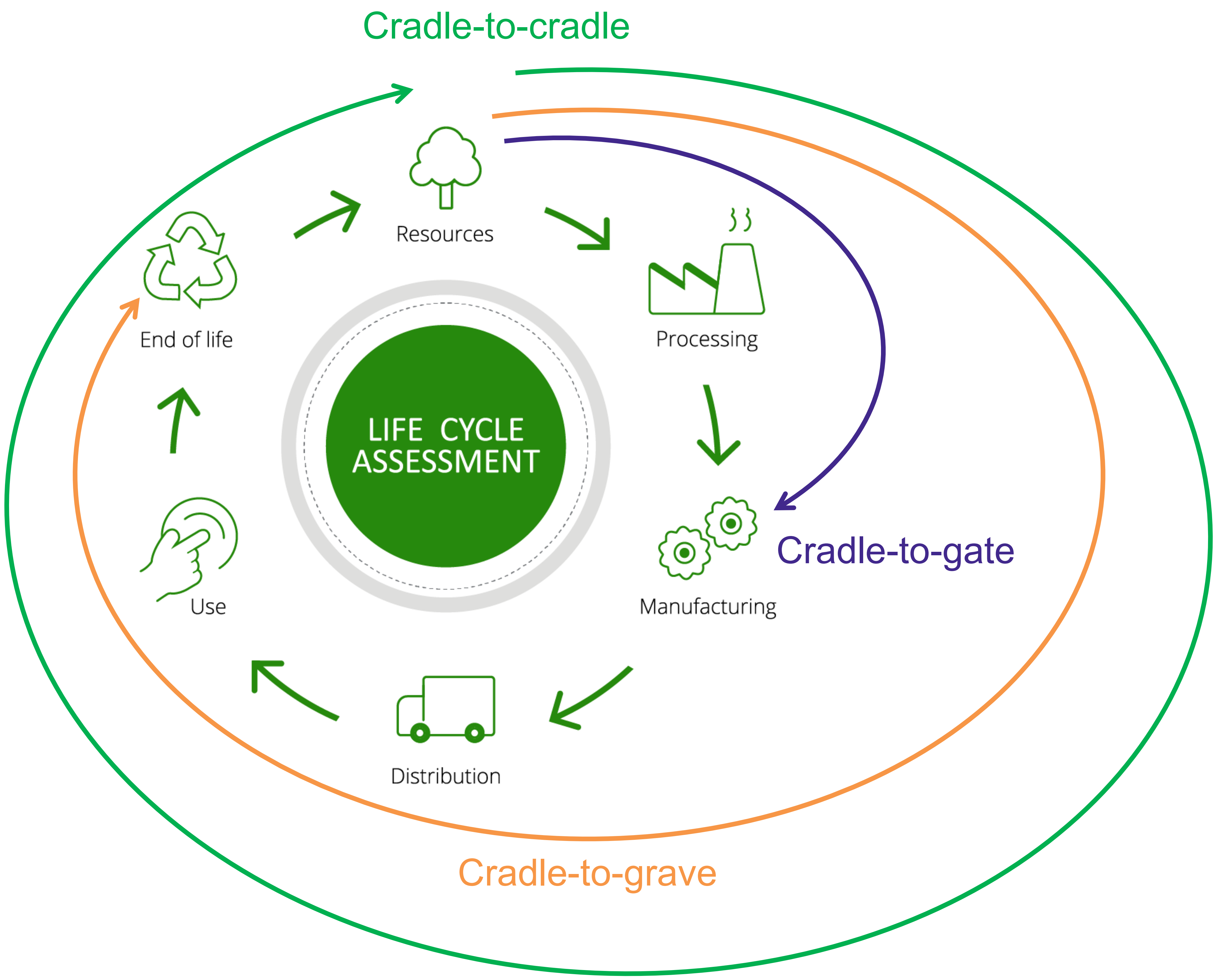
Life Cycle Assessment (LCA)

- ❑ Advantages
- ❑ Limitations: specific scnenario, not take into account for example cost, social…

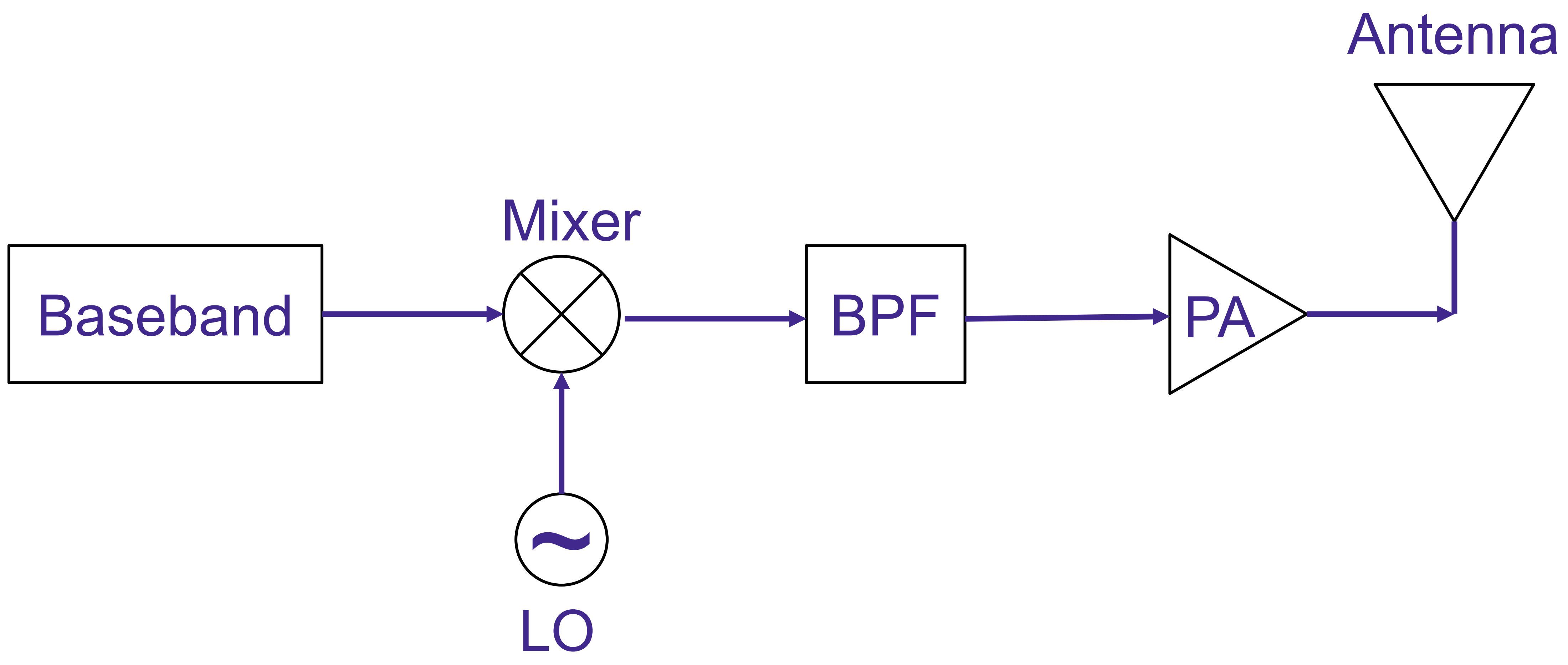
Some alternatives / complements to LCA

- ❑ Life Cycle Cost
- ❑ Environmental Impact Assessment
- ❑ Figure of merit / EP-score

Some LCA scopes



A general architecture of RF transmitter



Example: LCA of a phased array

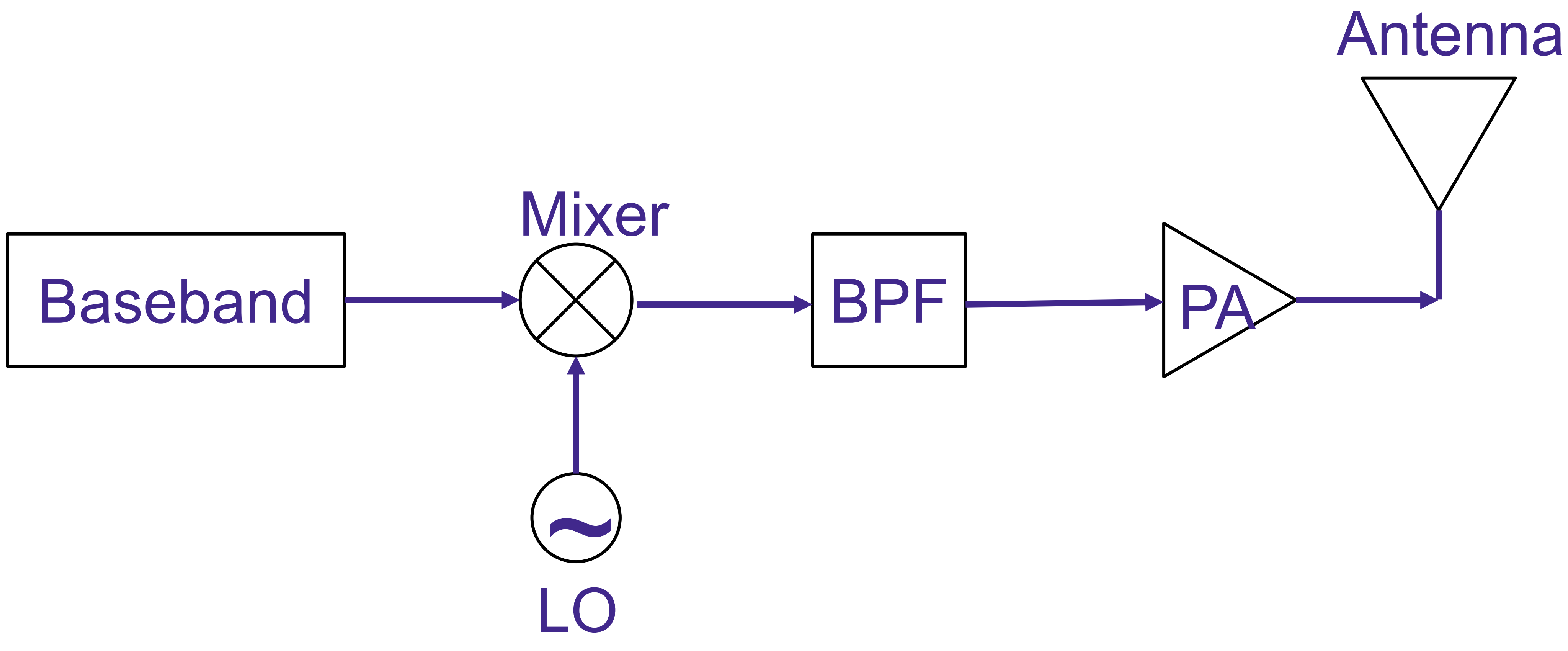


TABLE 1. LCA Inventory for the Phased Array Element, Based on More Advanced CMOS Nodes; the Lower Spec Option Is Detailed in the Dataset

Part	Part details from Sphera databases	#
PCB	PTFE, ENIG with gold plating: active circuit + antenna	40 cm^2
SMA connector	Model constructed based on the weight of an SMA metal body, gold plating, and PTFE dielectric	2
90nm RFIC (PA)	IC BGA 256 (2.62g) 27x27x2.36 CMOS logic (90 nm node) [based on models 2004-2014]	1
Cable	Cable 1-core signal 24AWG PTFE (3.0 g/m) D0.9	1
SMD L	Coil multilayer chip 0402 (1mg) 1x0.5x0.5	2
SMD C	Capacitor ceramic MLCC 0201 (0.17mg) 0.6x0.3x0.3 (Base Metals)	10

BOM for sub-6 GHz phased array

RFIC was ≈ using a logic process in 90 nm node

M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

Hotspot in IC fabrication

RFIC is the dominant factor ≈ 10× other contributions

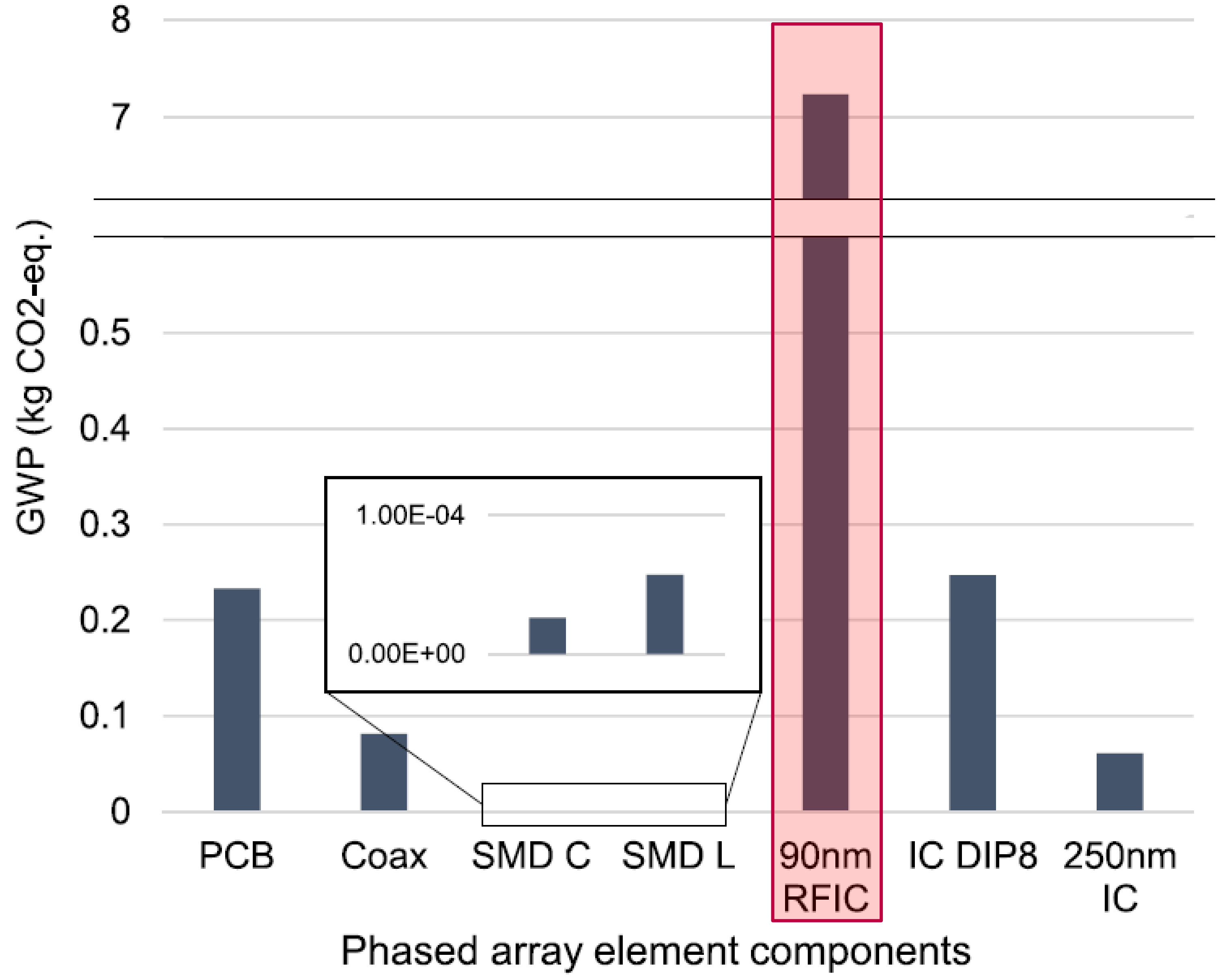
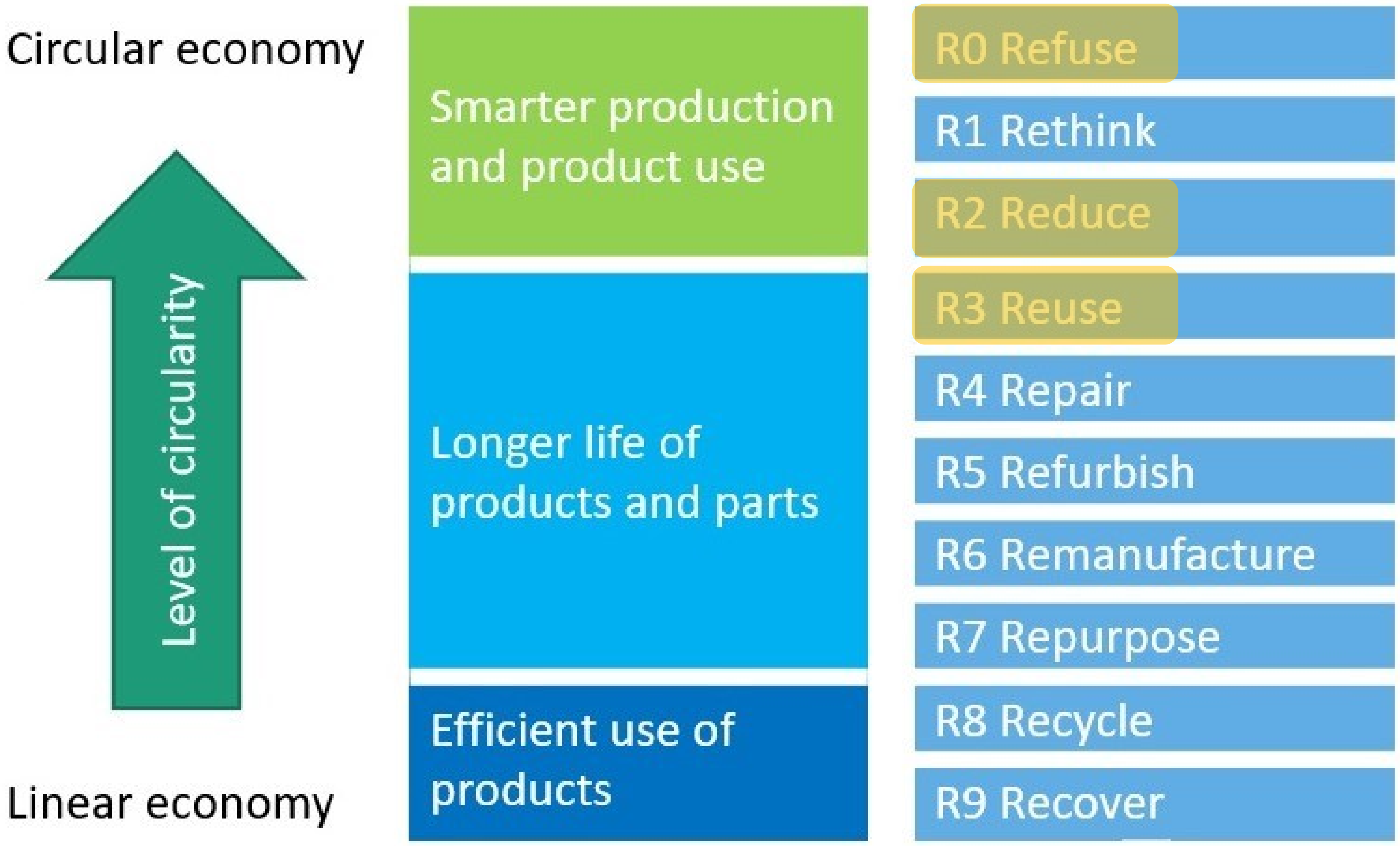


FIGURE 8. GWP for individual phased array elements, showing the effect of each component; a single 90 nm RFIC has > 5× the GWP of all other components.



https://www.econetworks.jp/en/2021/03/01/ce-2/

M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

How to reduce impact of IC ? – Chipless / Barcode

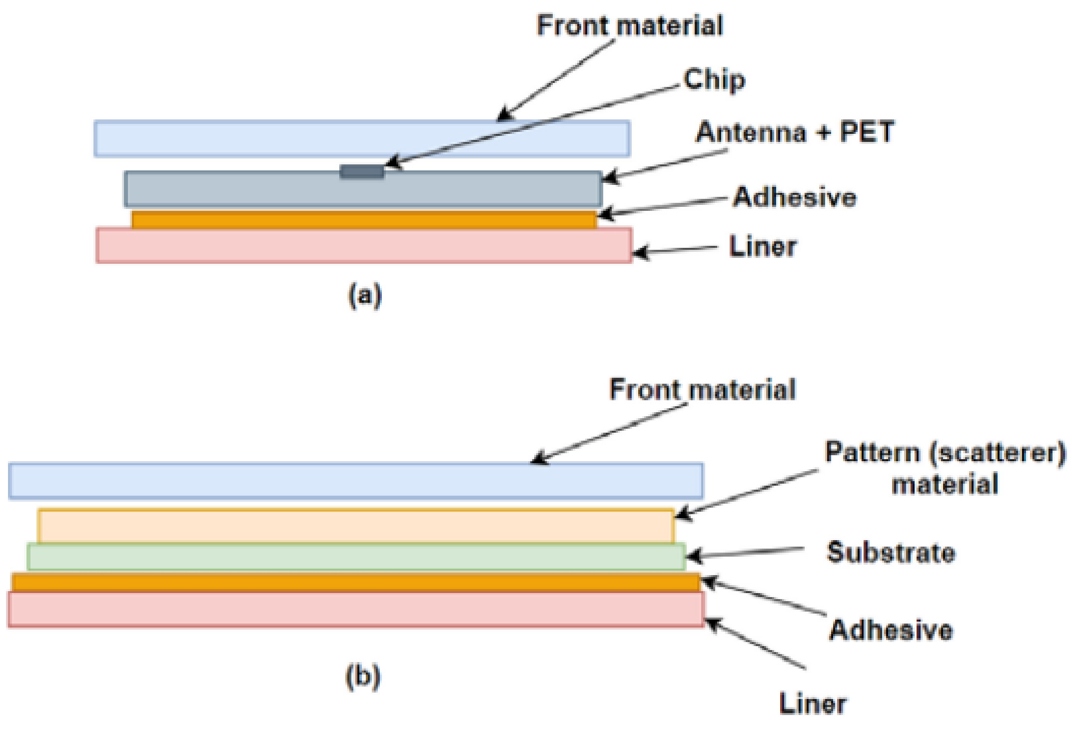
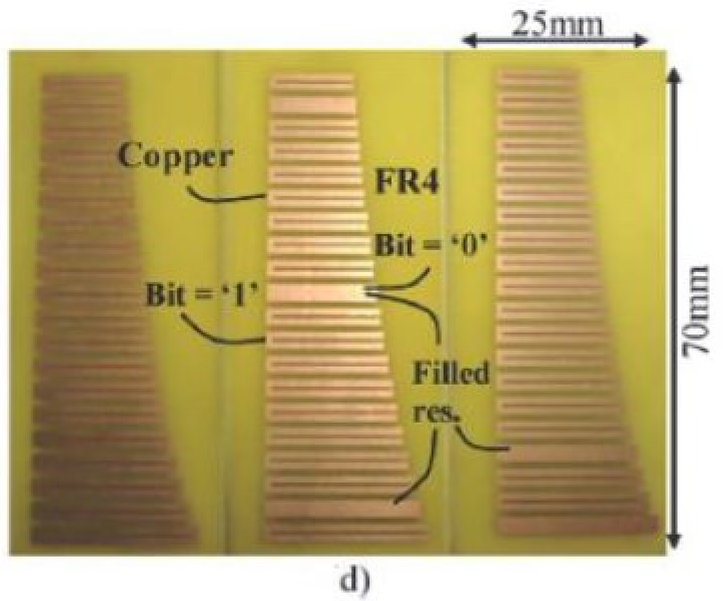
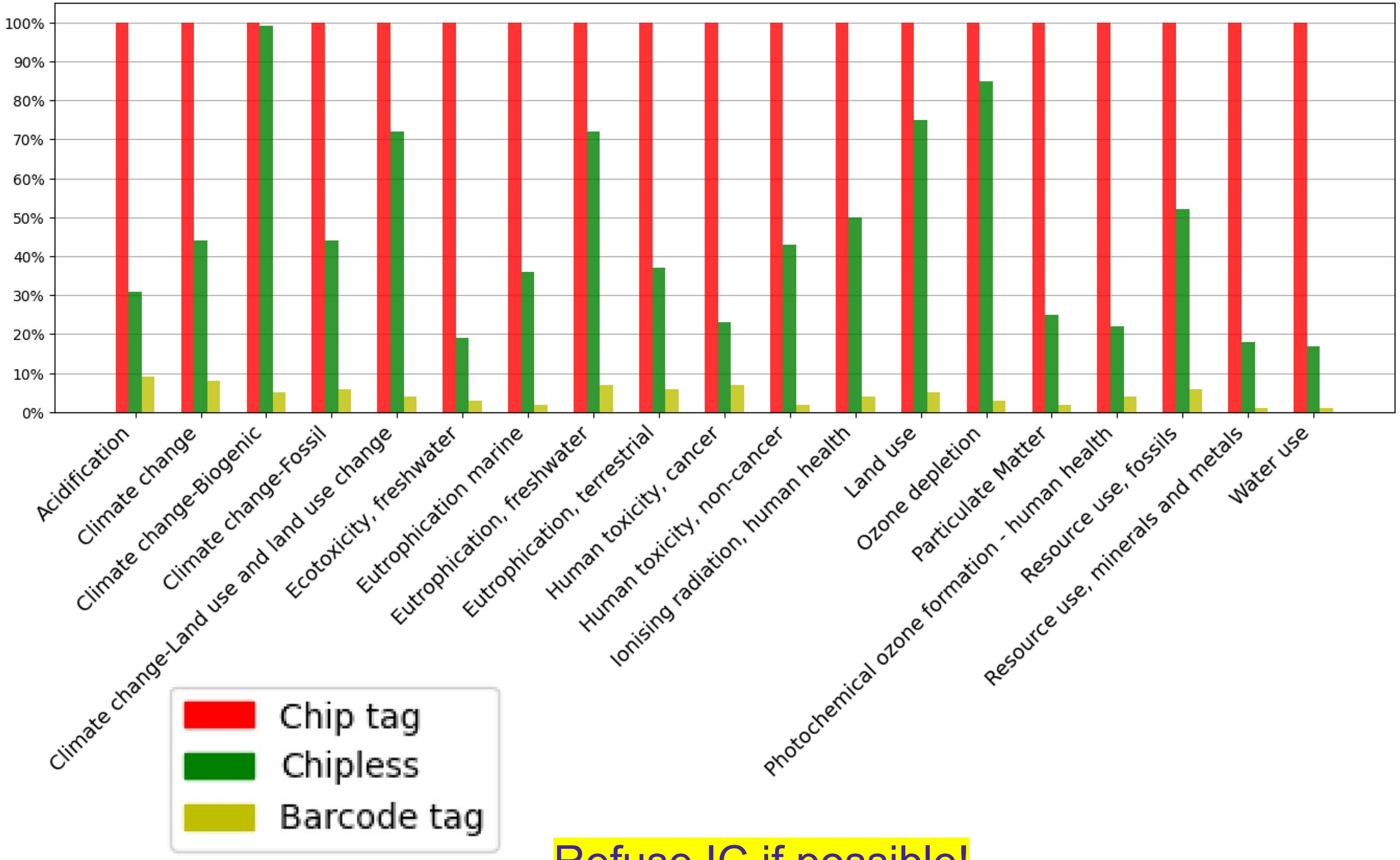


Fig. 3. Structure of (a) the UHF RFID tag (CCRR A61F 44x19 mm) under study and (b) the chipless tag.



Chipless RFID @LCIS



Refuse IC if possible!

L. Q. H. Nguyen and E. Perret, IEEE Journal of RFID

How to reduce impact of IC ? - Reduce

Older (less complex) CMOS process can reduce environmental impact **from fabrication point-of-view**

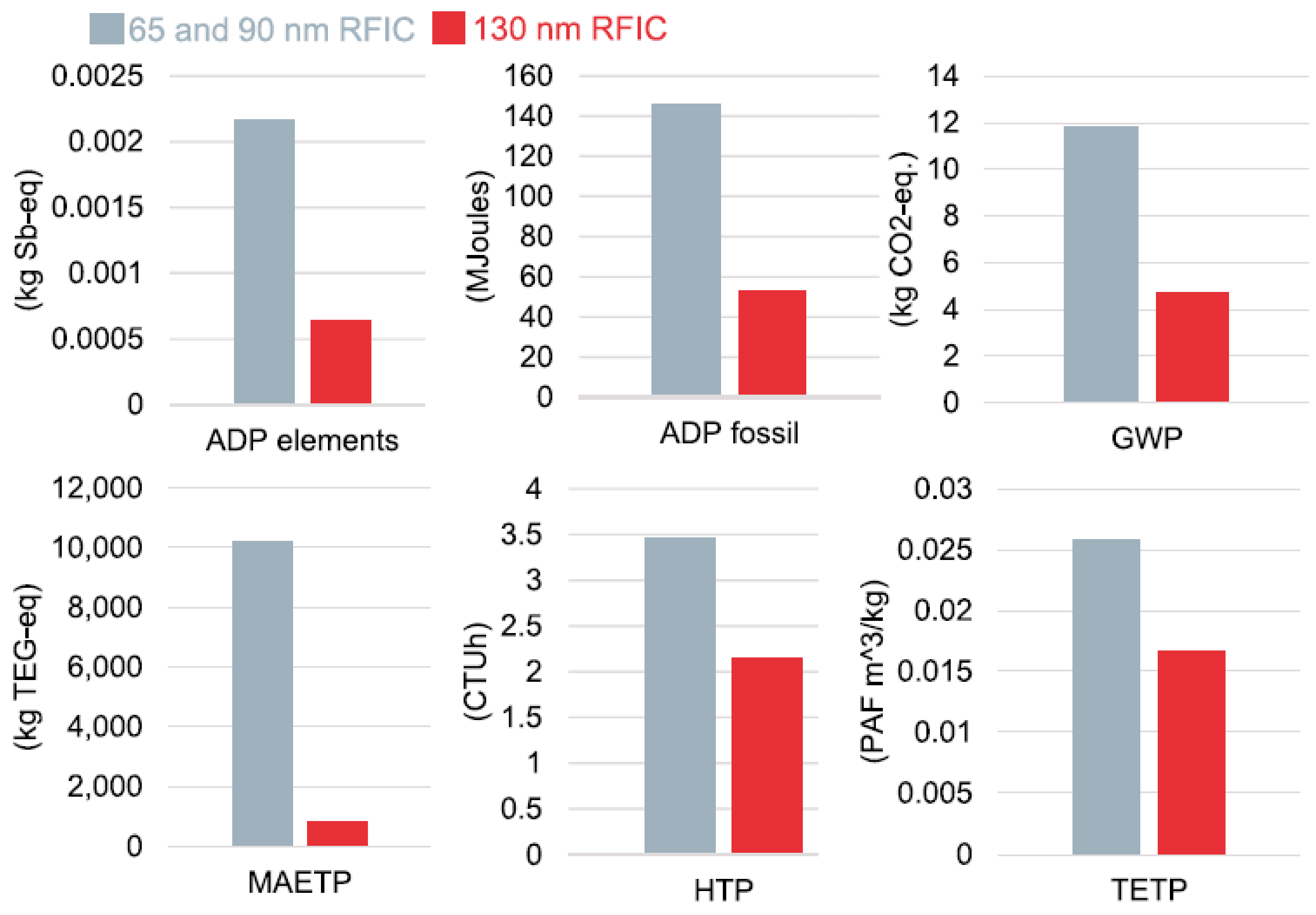
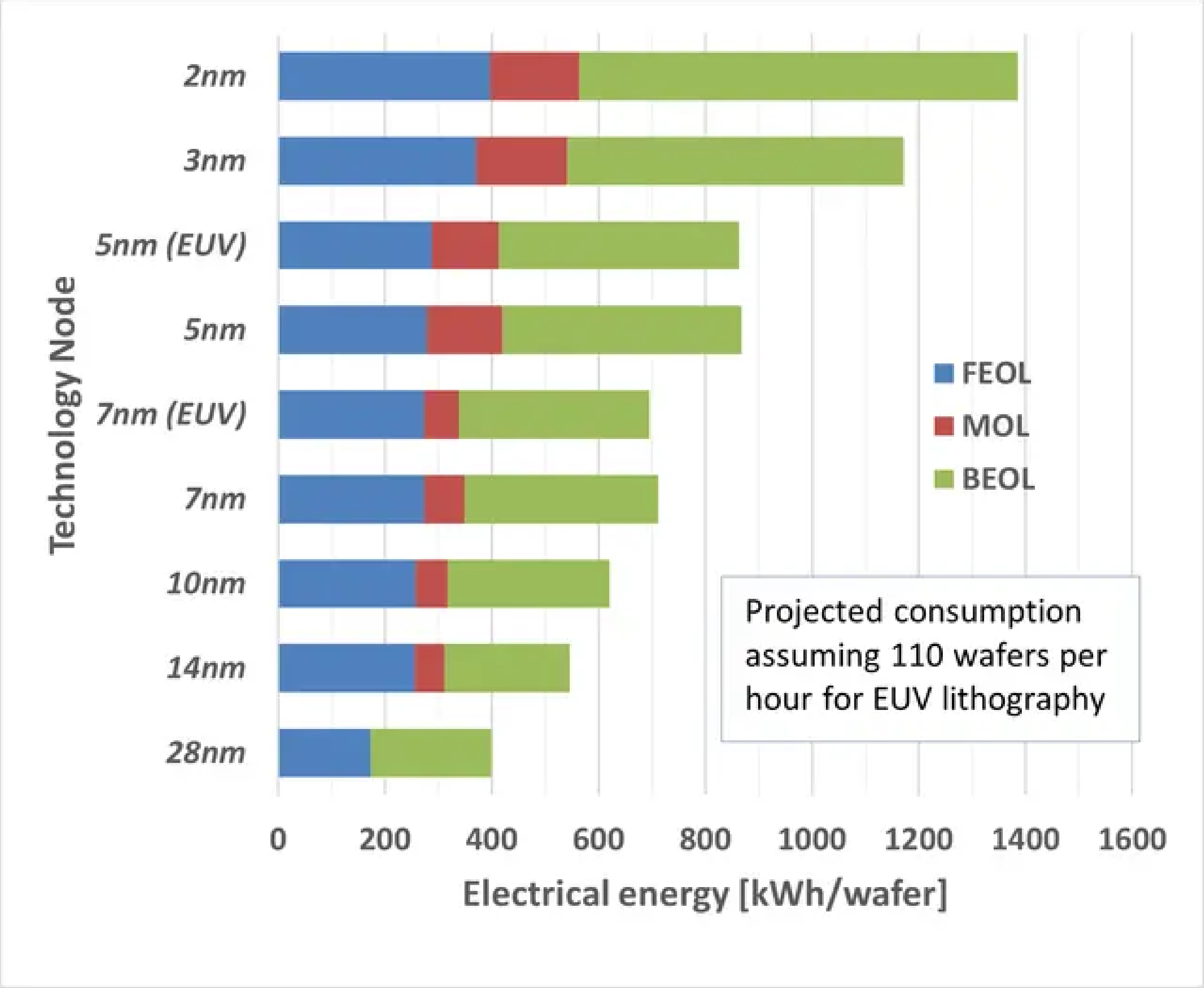


FIGURE 9. LCA outputs for individual phased array circuits (i.e. one array element, including the antenna), showing the impact of changing the IC process to an older CMOS process.



M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

https://www.imec-int.com/en/articles/environmental-footprint-logic-cmos-technologies

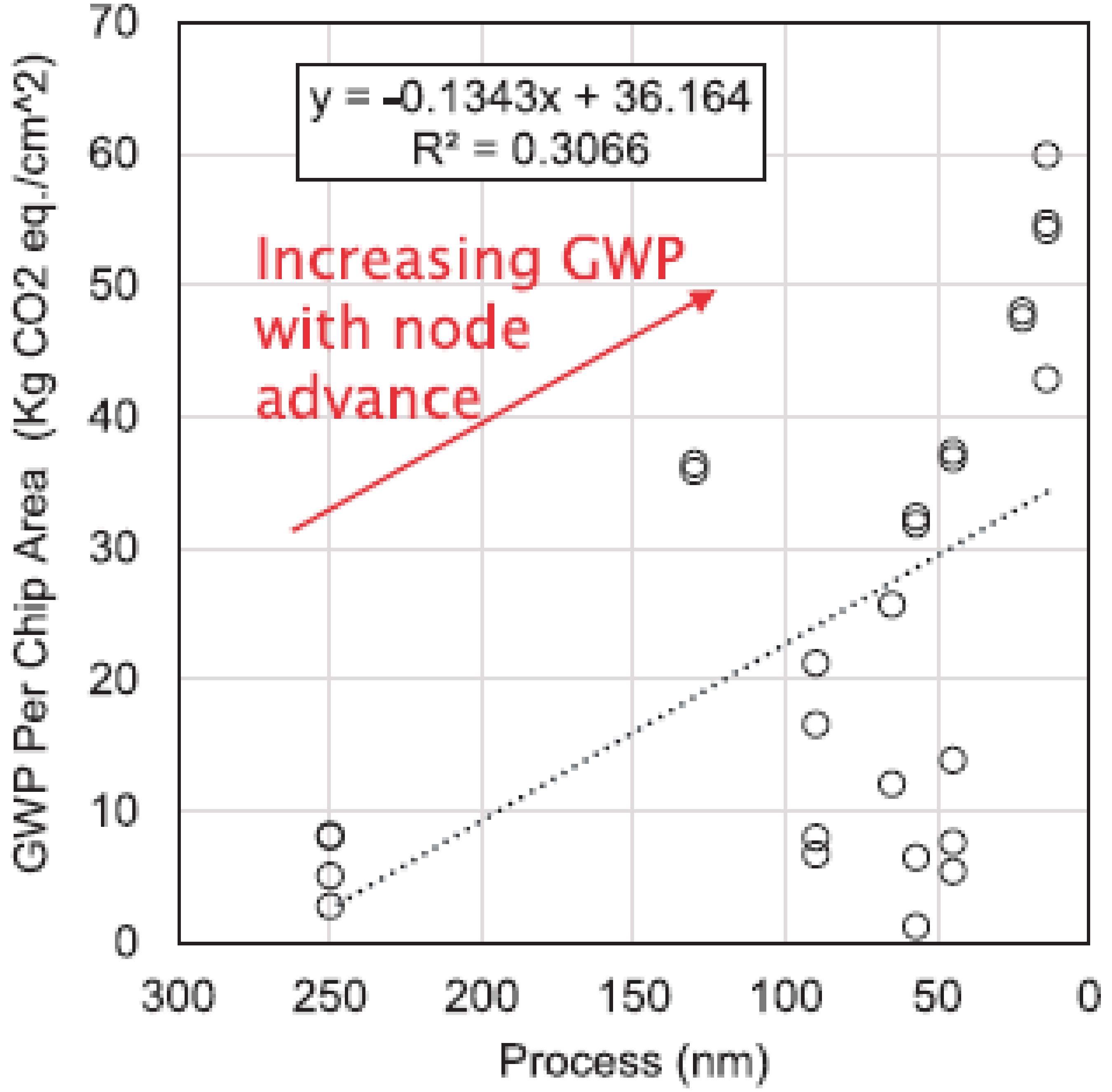
Effect of CMOS process

How To include resilience + critical factor?

How about power consumption?

$$t_I = \frac{M_1 - M_0}{P_0 - P_1} \quad t_B = \frac{M_1}{P_0 - P_1}$$

Donald Kline Jr. *et al., Sustainable Computing: Infomatics and System*



$$FoM = \frac{\Delta(CO2eq)}{\Delta P}$$

At which point we reach the compromise fab vs usage?

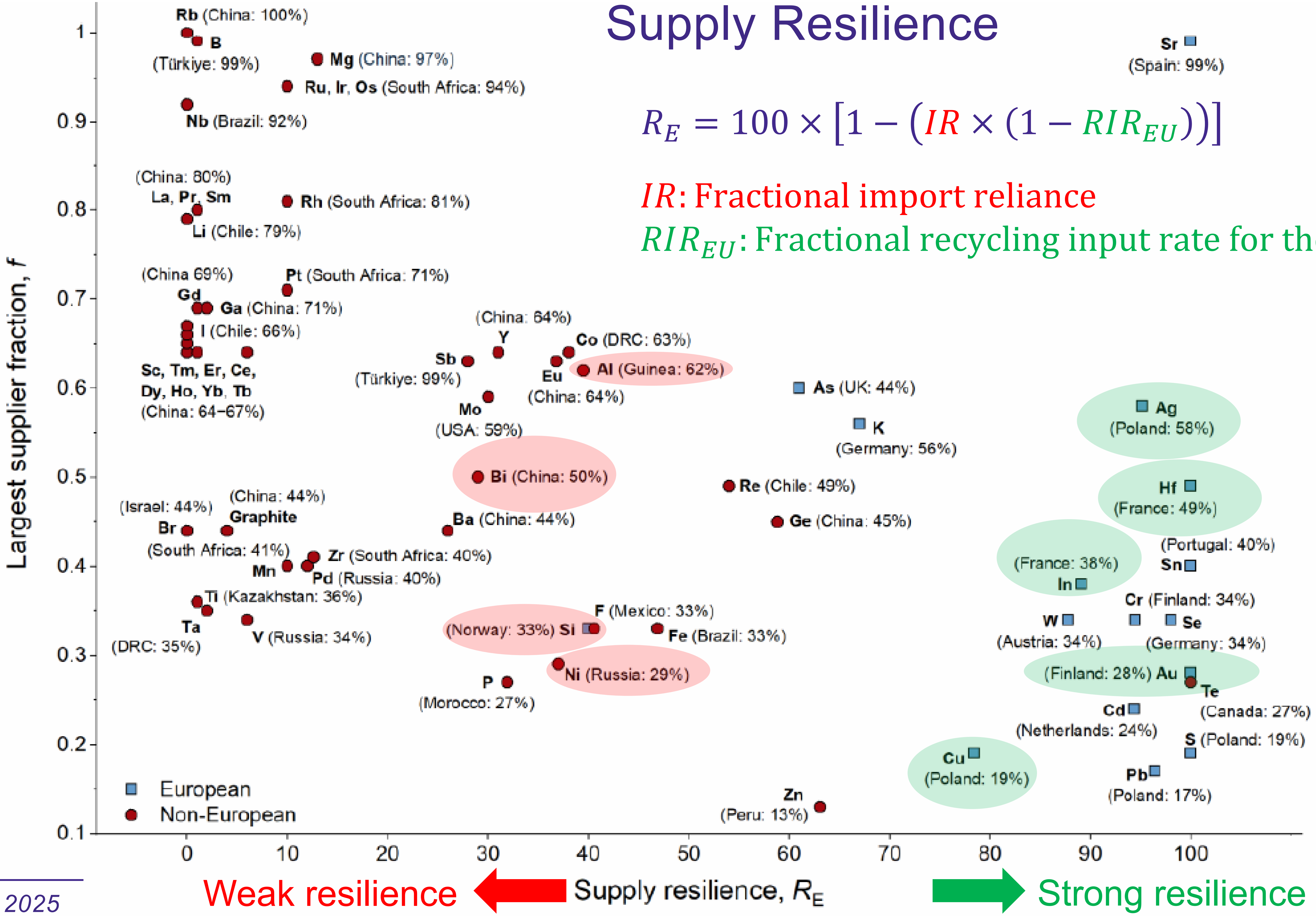
⇒ Convert power consumption ↔ kg CO2eq

$$FoM = \frac{\Delta(CO2eq - fab)}{\frac{\Delta(CO2eq - use)}{1days} \times active\ days}$$

P can be defined as the required power to process the same amount of computing

M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

Supply Resilience



$$R_E = 100 \times \left[1 - \left(IR \times (1 - RIR_{EU})\right)\right]$$

IR: Fractional import reliance

RIR_{EU}: Fractional recycling input rate for the EU

C. Teixeira *et al., 2025*

How to reduce impact of IC ? - Reuse

Variation < 0.1 dB/cm

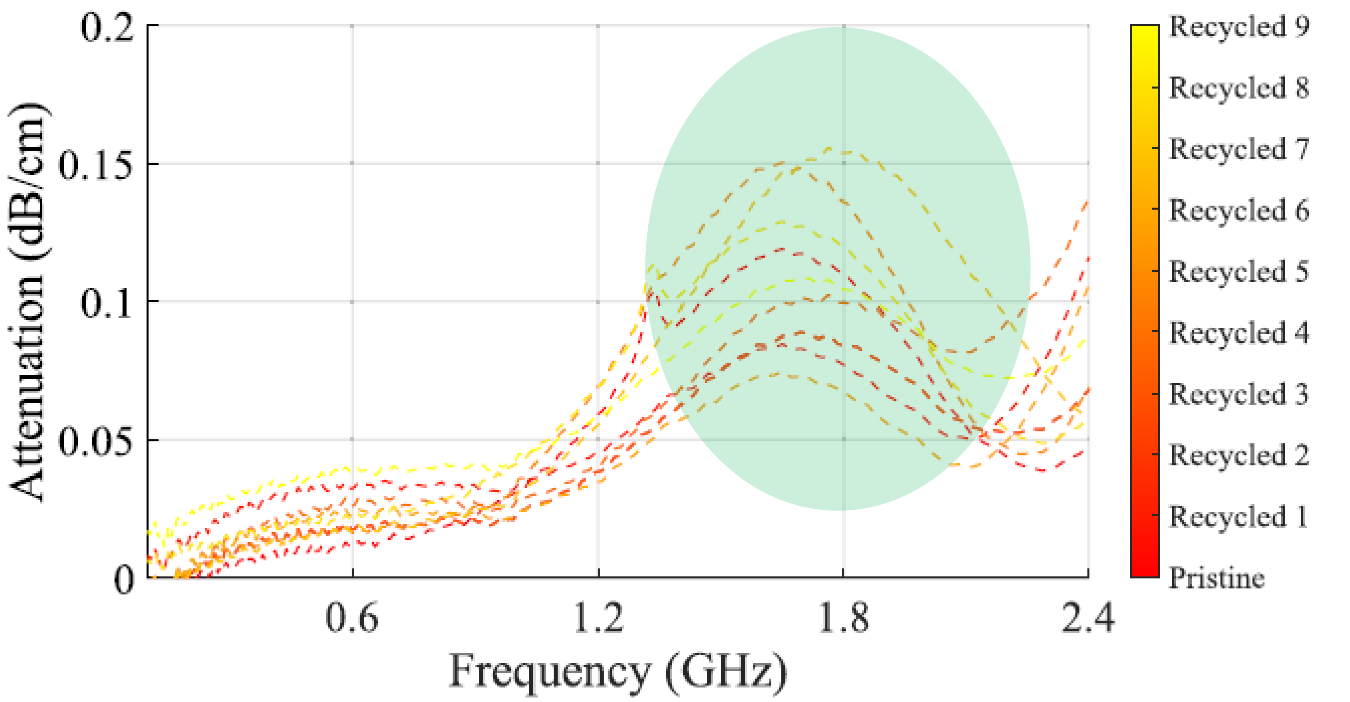
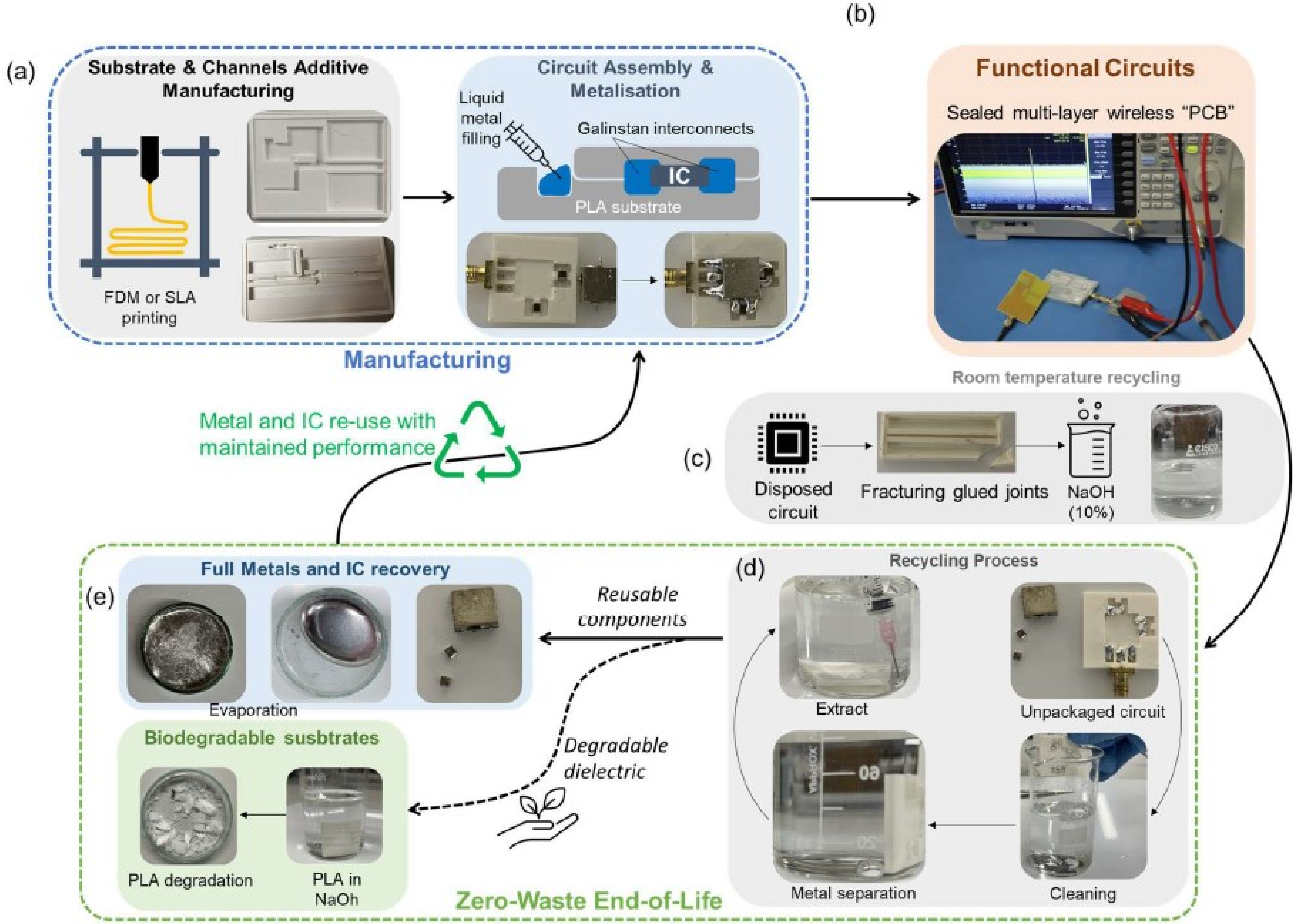


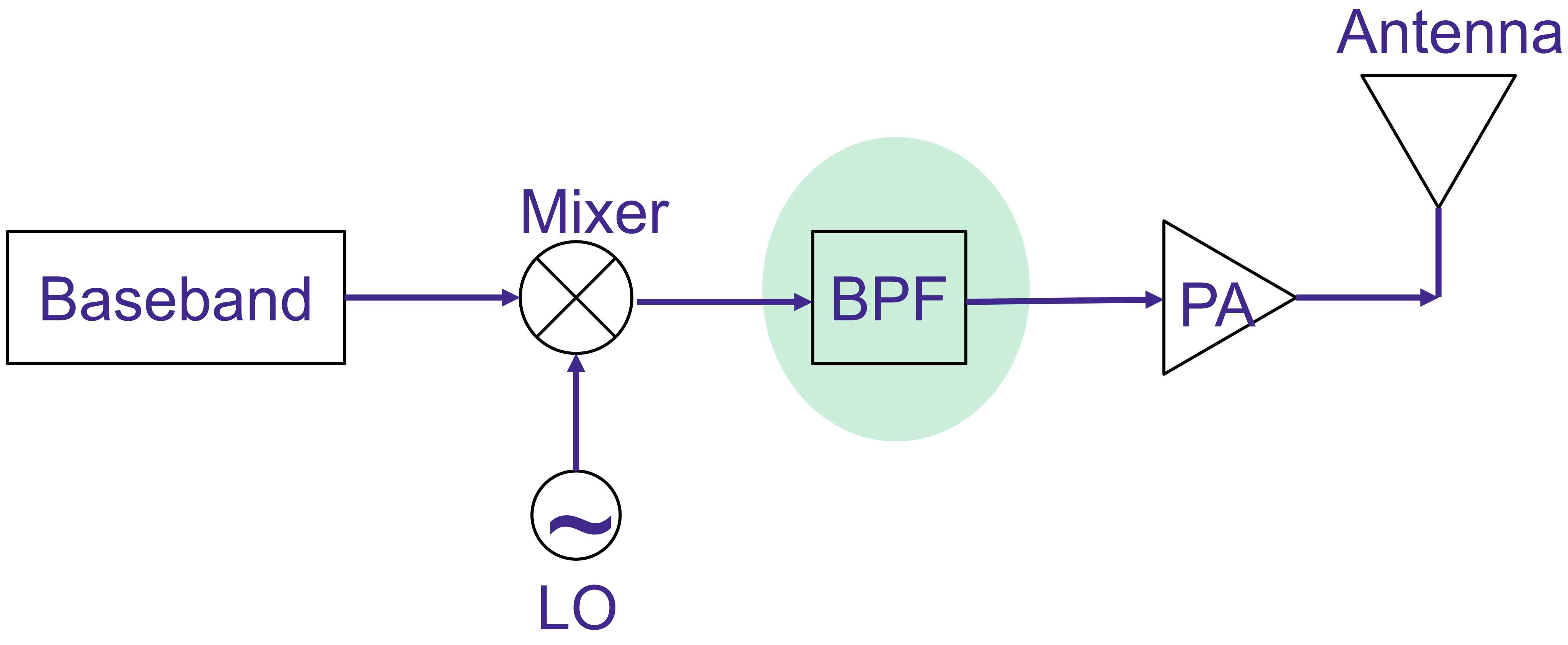
Fig. 3. Repeatability ($n = 9$) of the measured liquid metal based lossy transmission line representing by attenuation.

Scalability
Data privacy



X. Fang and M. Wagih, IEEE Transaction on Circuits and Systems – I, 2025

Example: LCA of bandpass filters



Back in 2022…

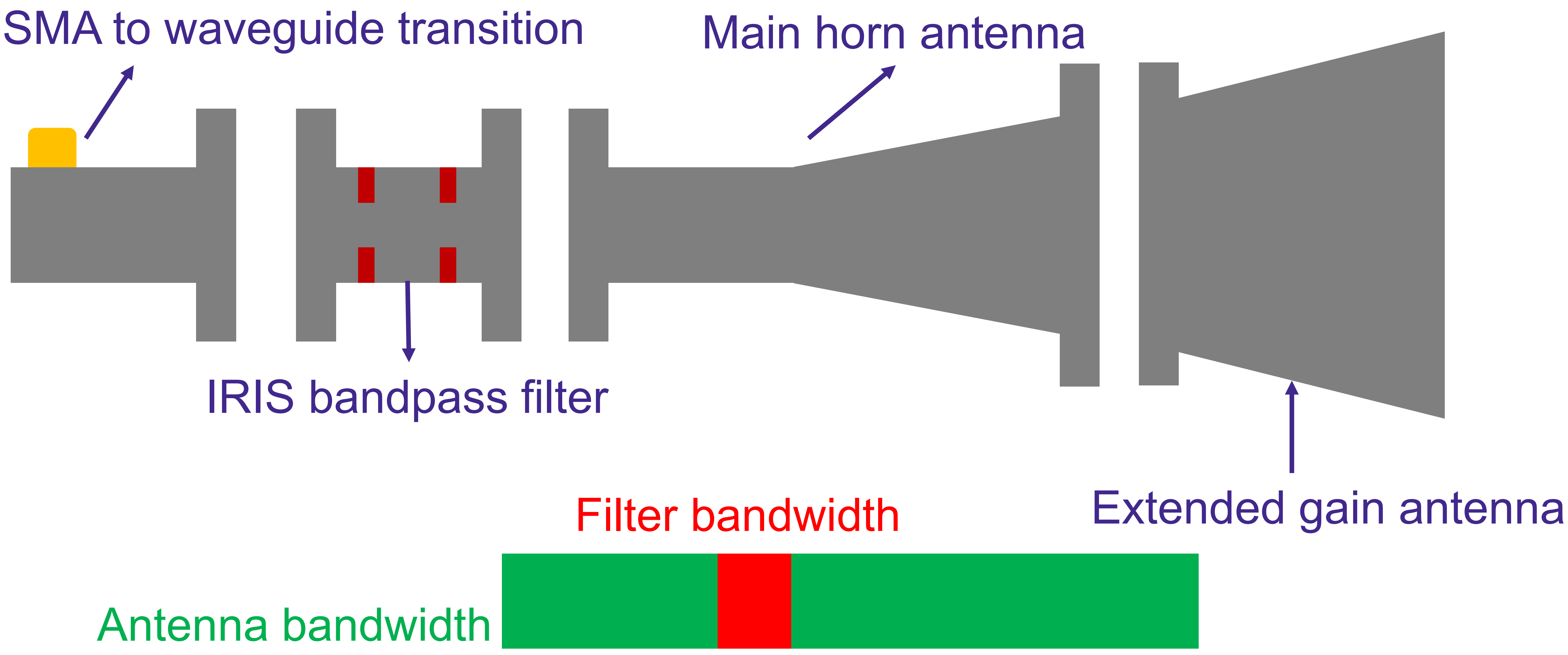
Projet 1A - Legos pour dispositif passif radiofréquence

Modélisation et conception d'antennes modulables

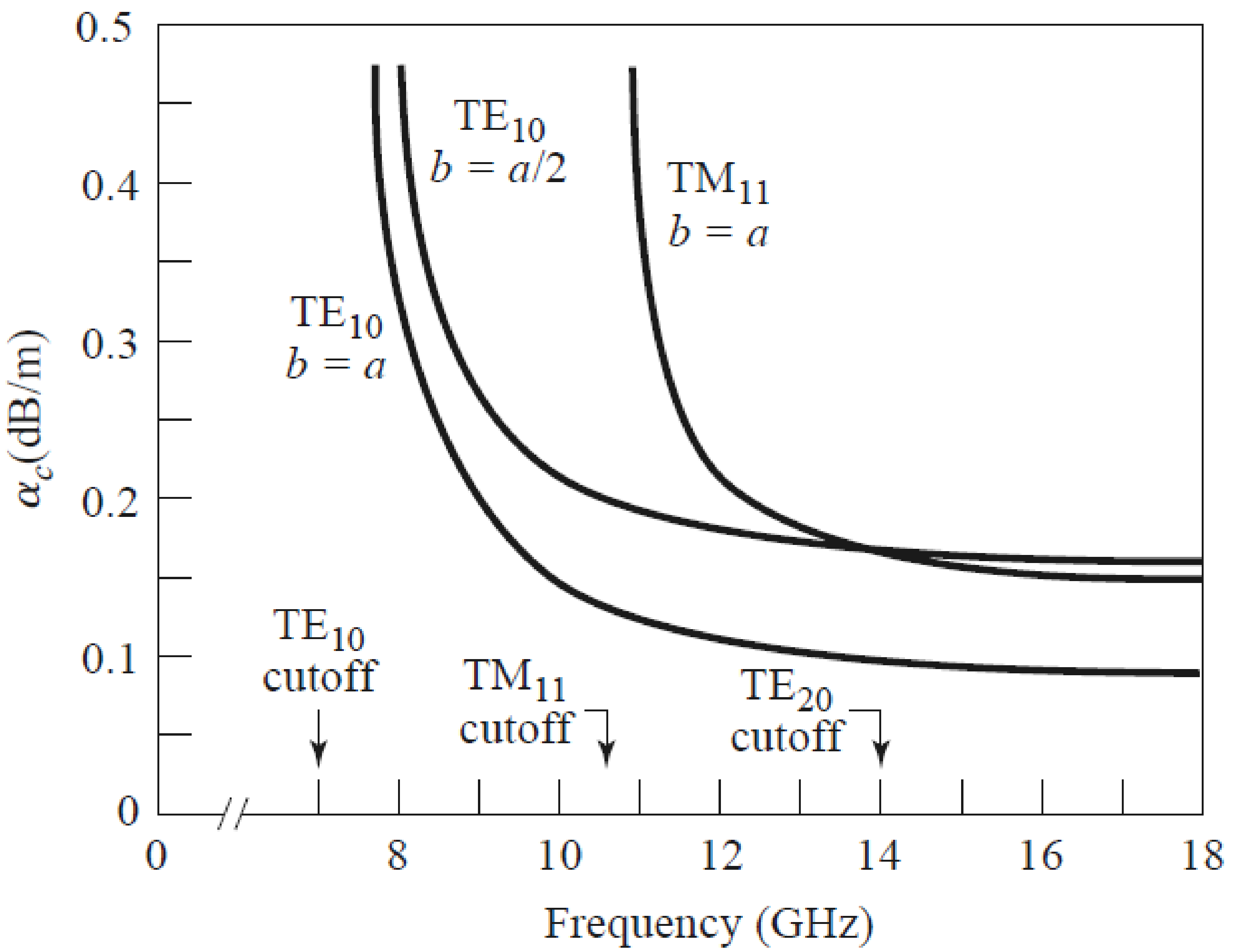
ETUDIANTS
Juliette Nebon
Axel Tussau
Lisa Duguet
Loris Apparu
Malou Cattaneo
Montaine Jamet
Paco Gerbier

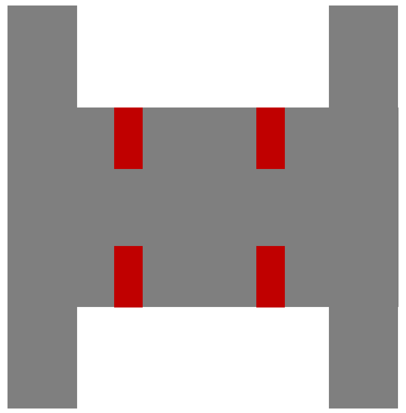
ENCADRANTS
Tan-phu Vuong
Nhu-huan Nguyen

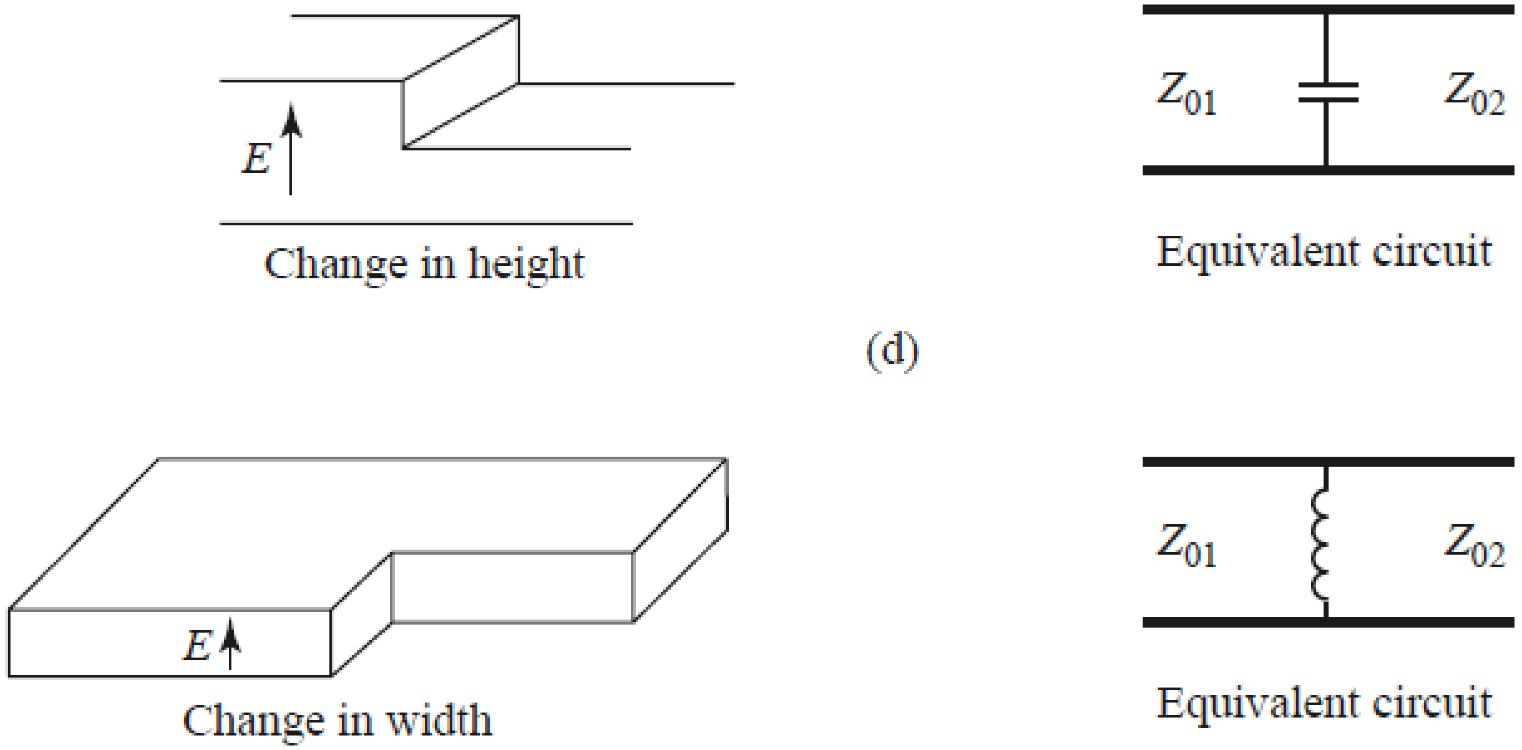
- ✓ Wideband antenna: main antenna + extended gain, can be exchanged
- ✓ IRIS bandpass filter: operate at a specific band, can be exchanged
- ✓ SMA to waveguide transition
- ✓ Assembled by screws



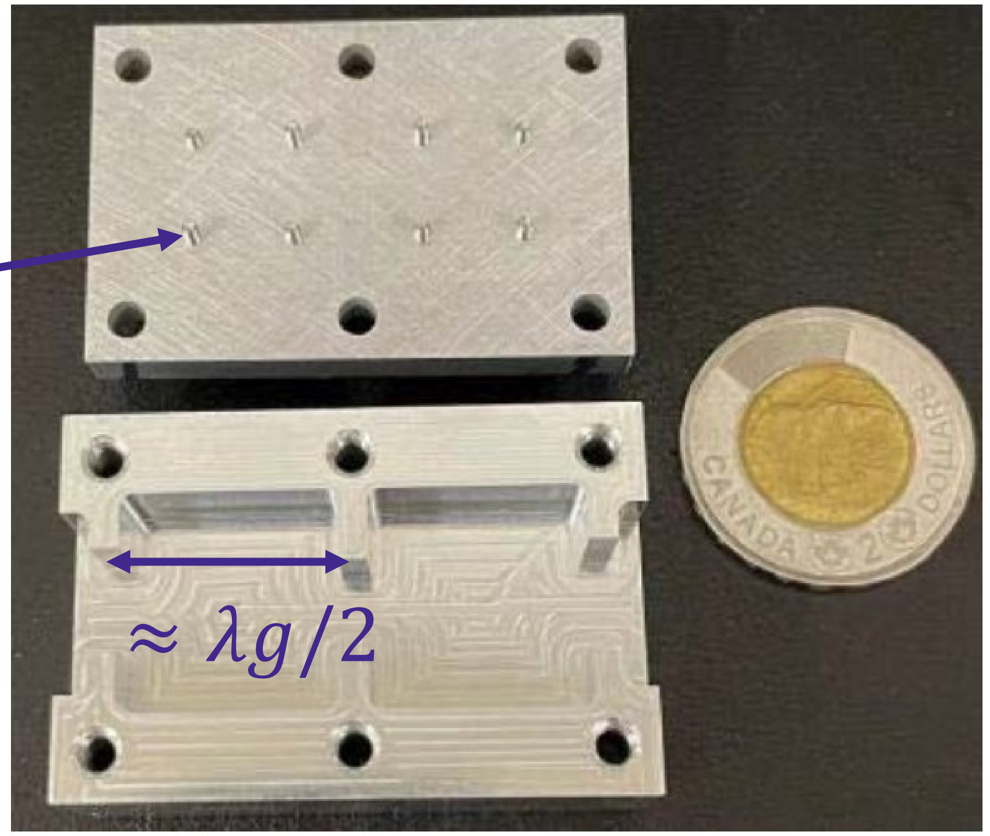
IRIS bandpass filter

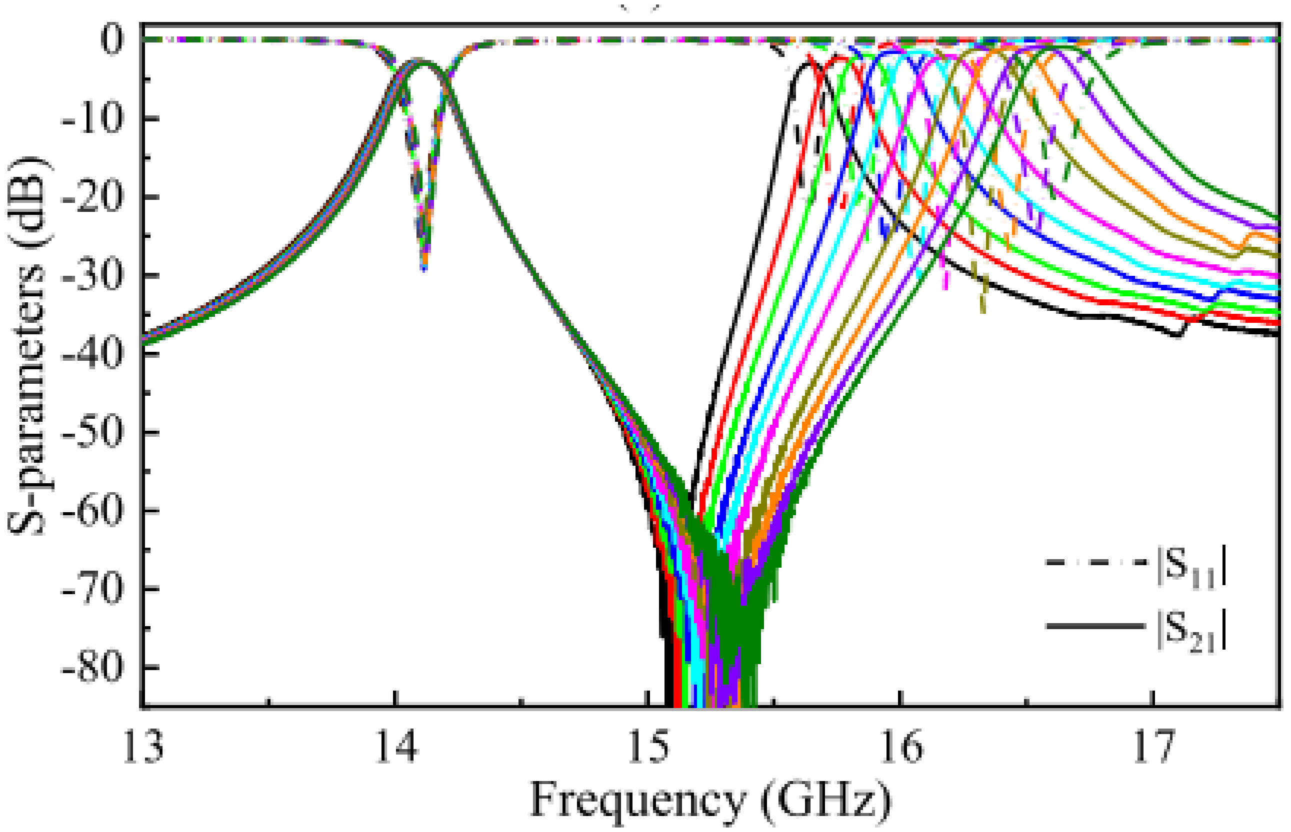






Tuning screws



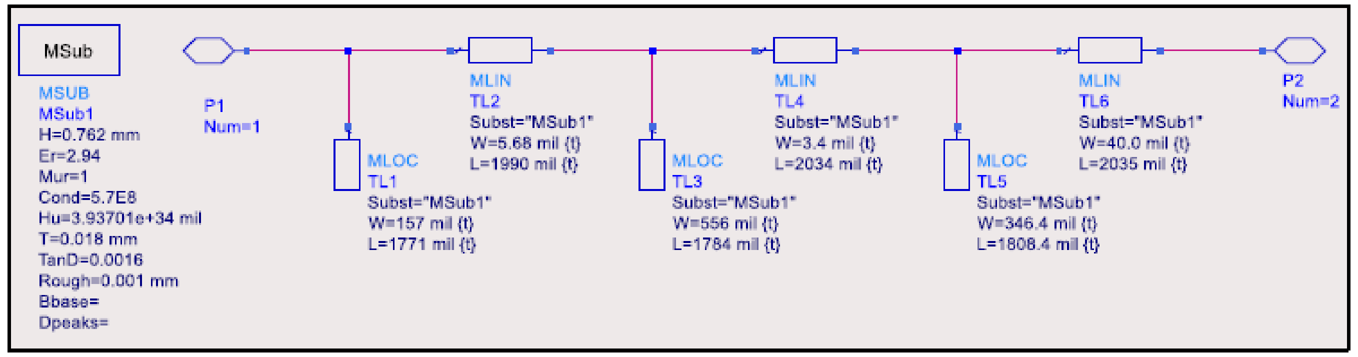


Reconfigurable bandpass filter

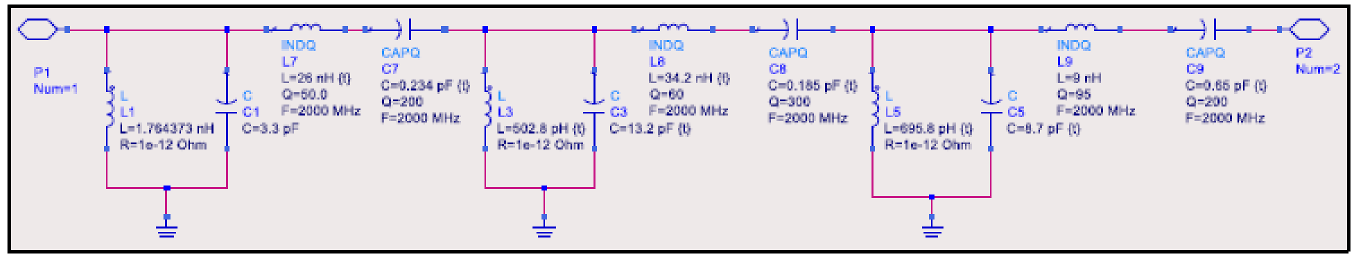
David M. Pozar, Microwave Engineering

Wentao Lin *et al.*, IEEE T-MTT 2023

Example: LCA of bandpass filter: Performance vs active life time



(b)



(c)

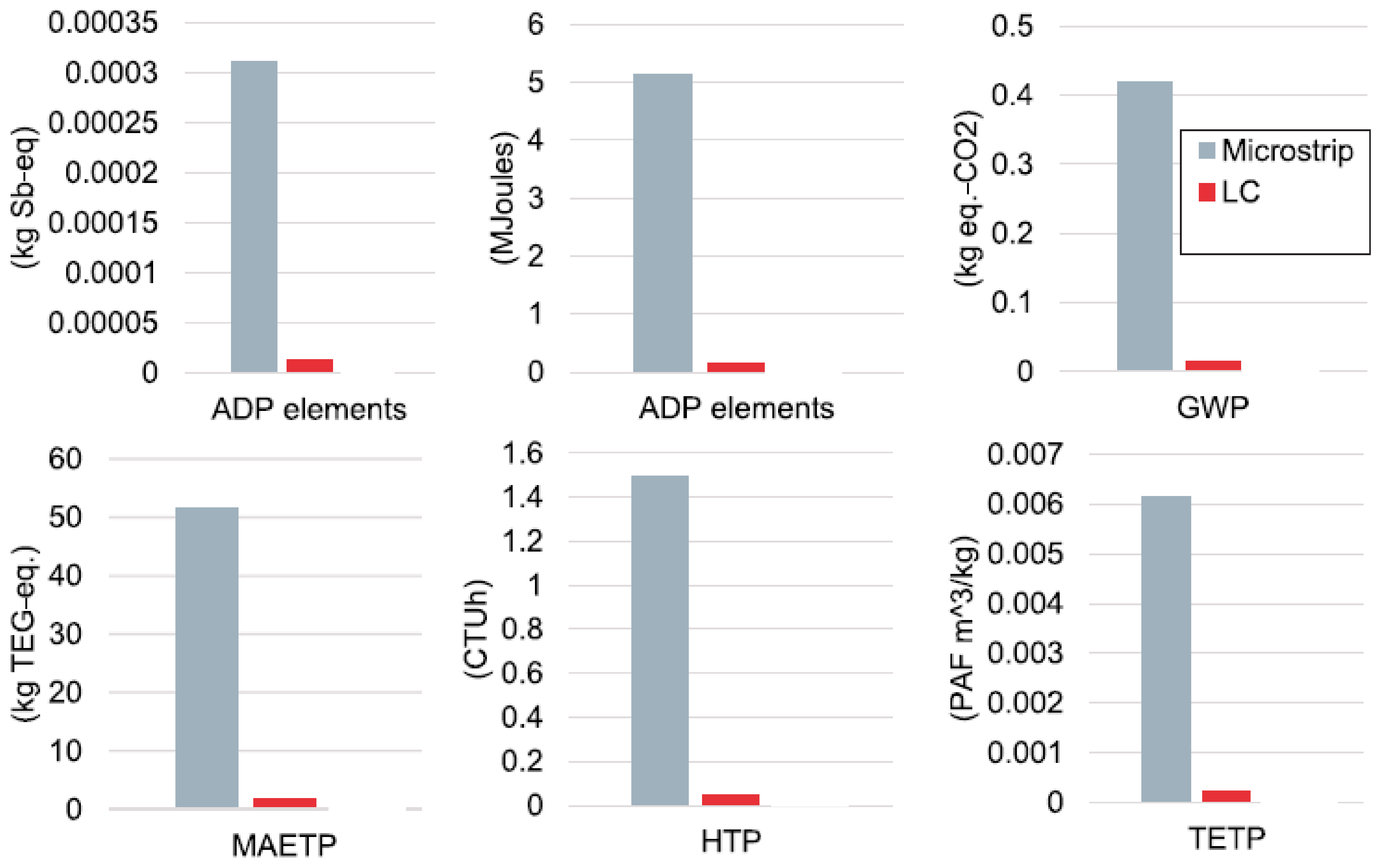
Distributed elements microstrip filter

Part	Part details from Sphera databases	#
PCB	PTFE, ENIG with gold plating	72 cm^2

Lumped elements filter

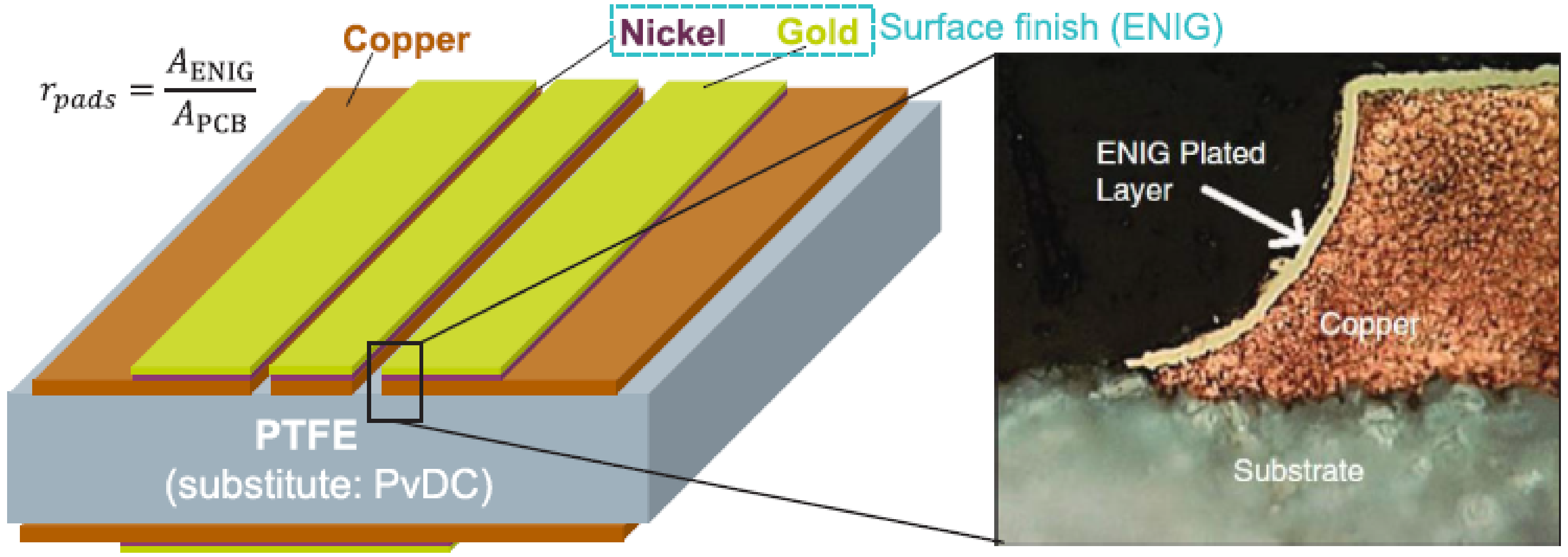
Part	Part details from Sphera databases	#
PCB	PTFE, ENIG with gold plating	1 cm^2
SMD L	Coil multilayer chip 0402 (1mg) 1x0.5x0.5	6
SMD C	Capacitor ceramic MLCC 0201 (0.17mg) 0.6x0.3x0.3 (Base Metals)	6

Microstrip has higher environmental impact in fabrication point of view due to larger PCB area + gold plating



M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

Example: Reduction of materials



Performance = ?

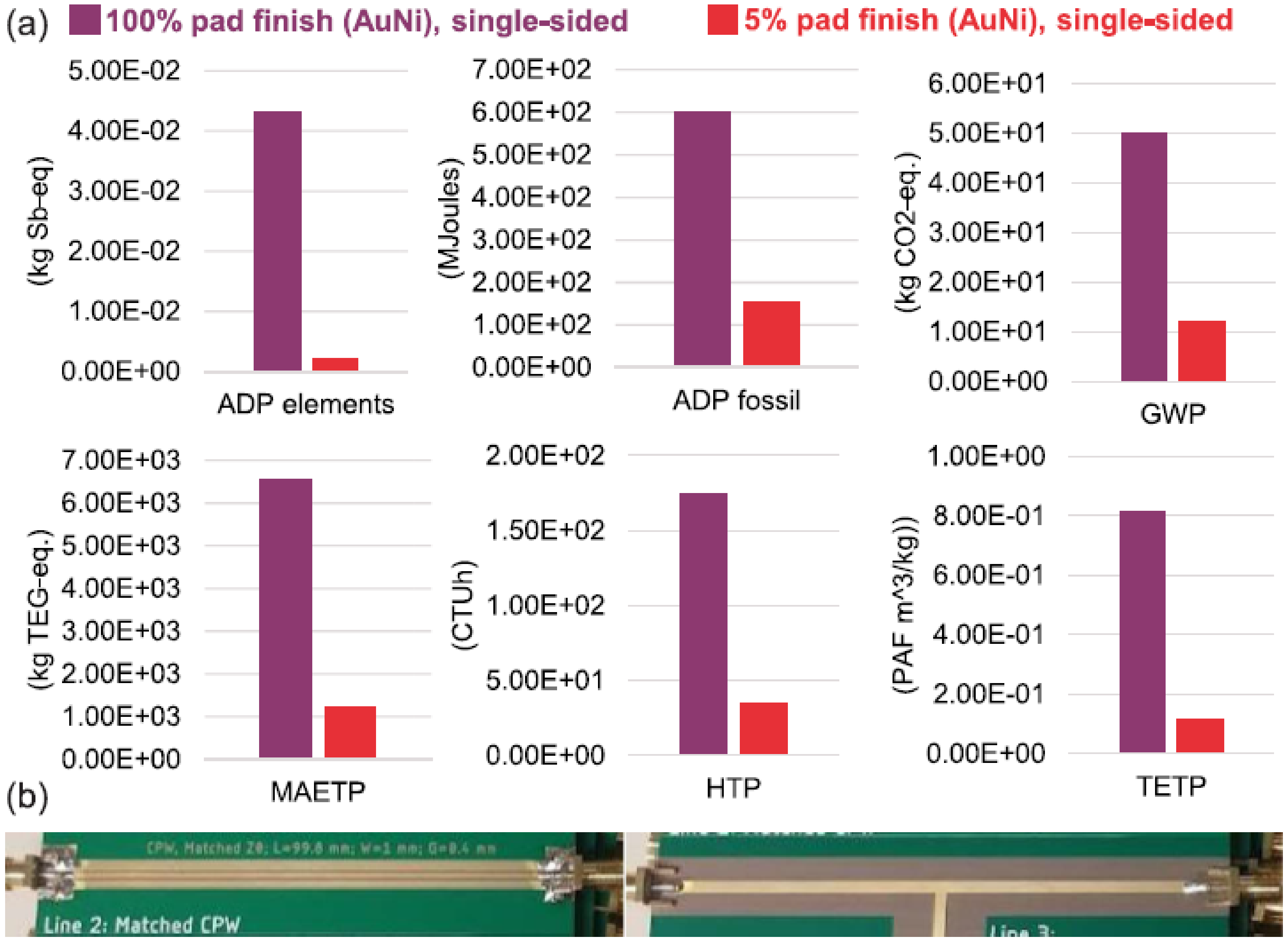


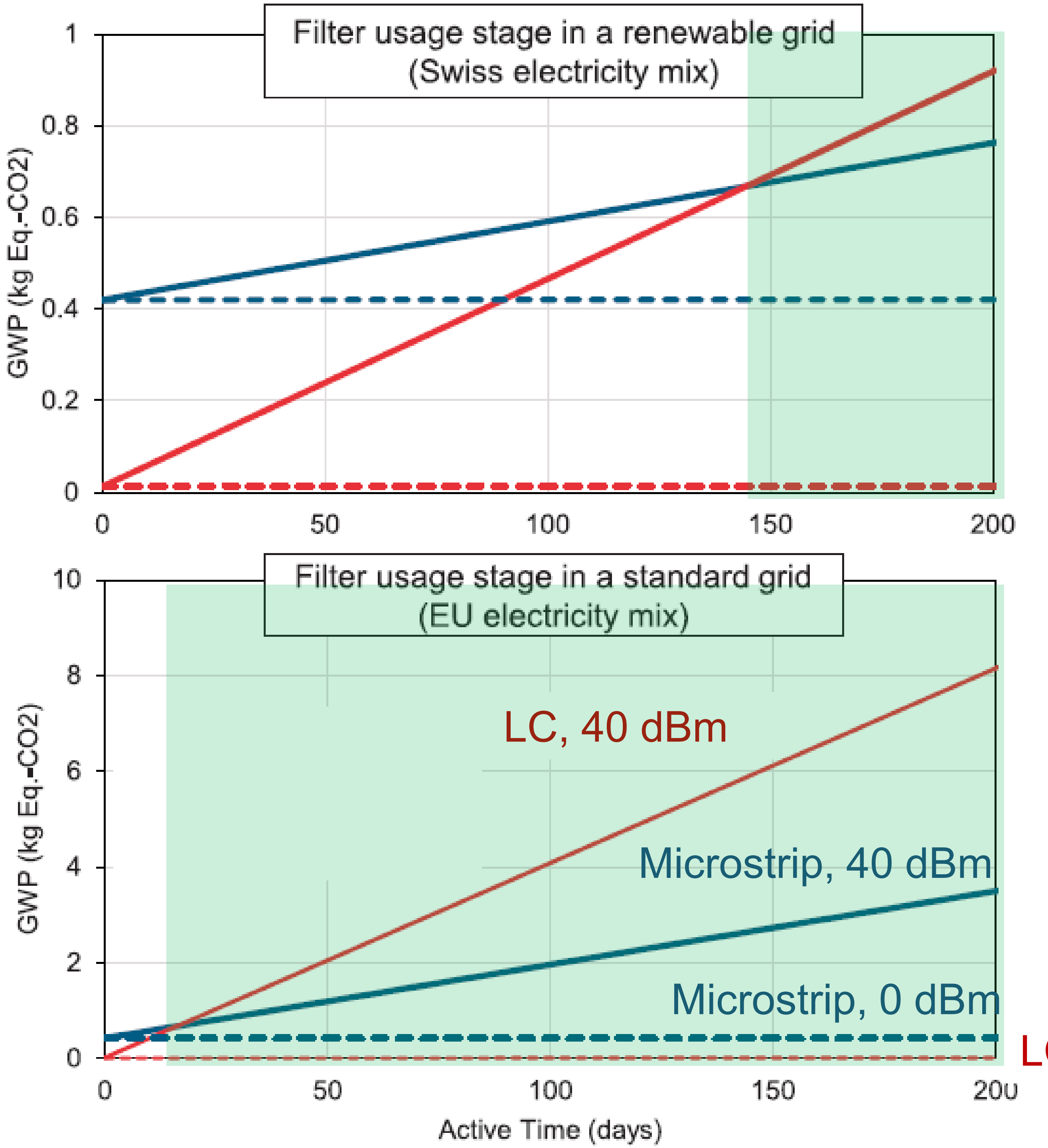
FIGURE 3. Outputs of the (a) LCA outputs for varying surface finish coverage (i.e. 200 nm of gold in ENIG-coated traces); (b) example CPW and microstrip lines on a low-cost Teflon substrate with ENIG surface finish around the line.

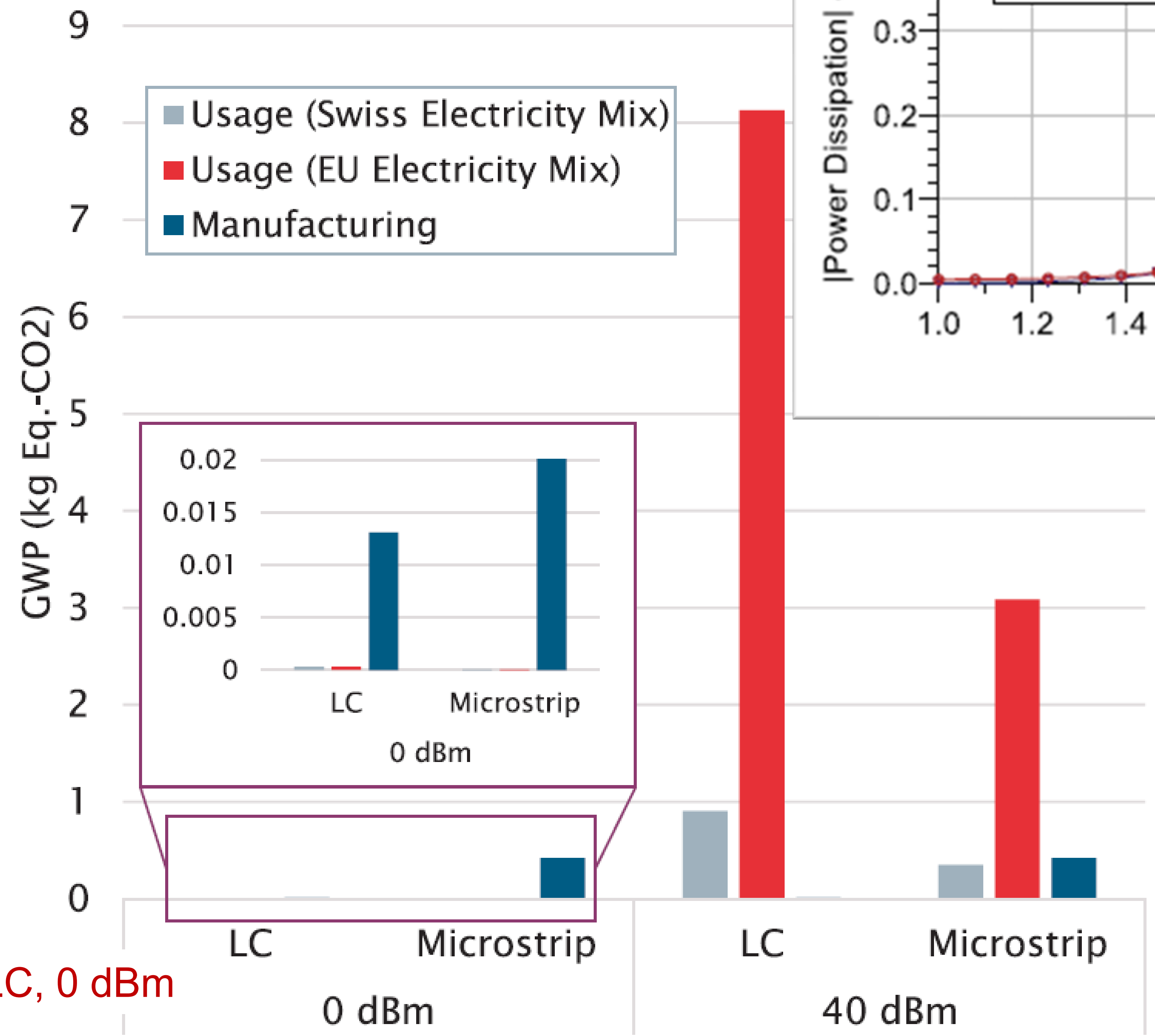
M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

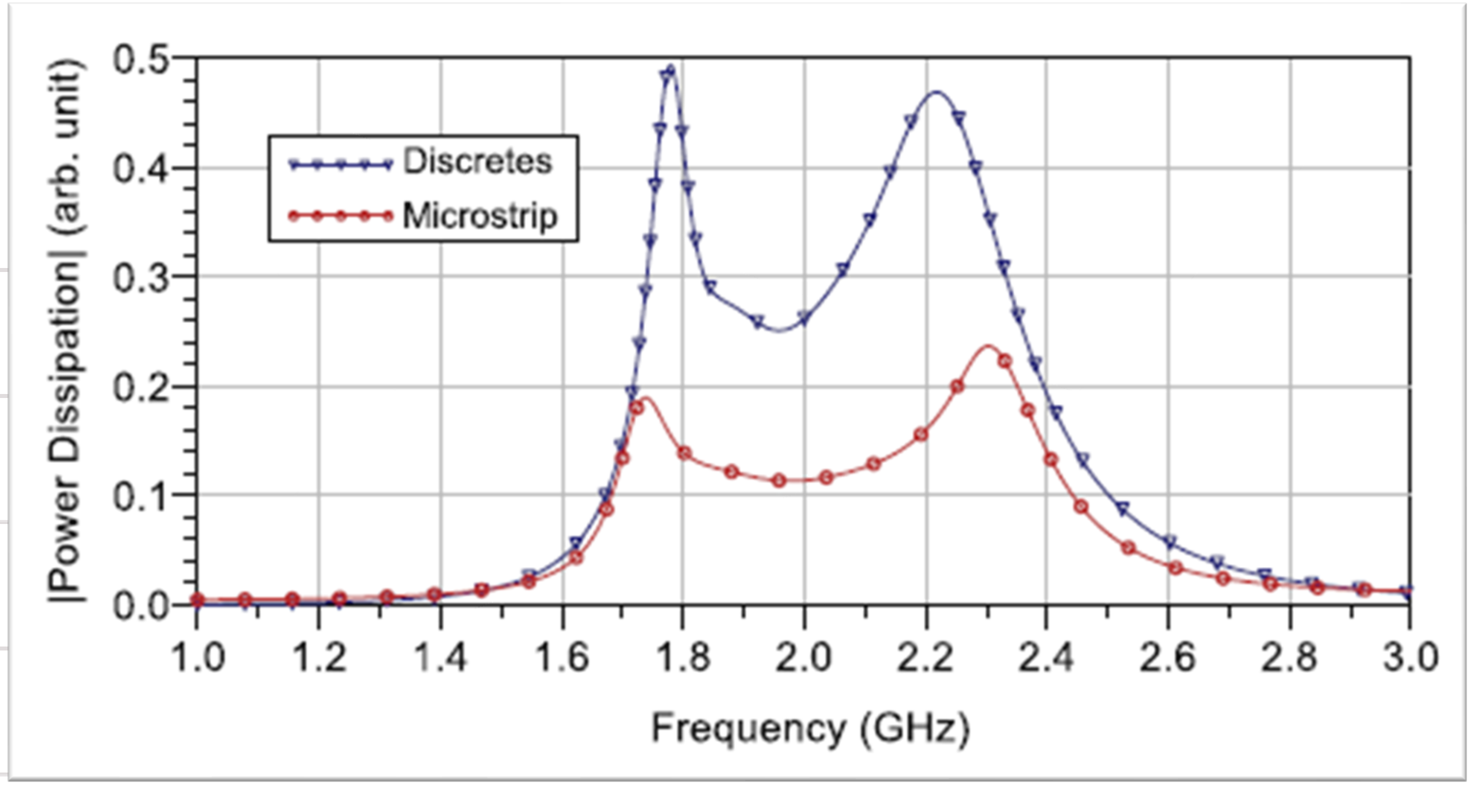
Example

But this story is changed with active life time...

and depends where we use our circuits…





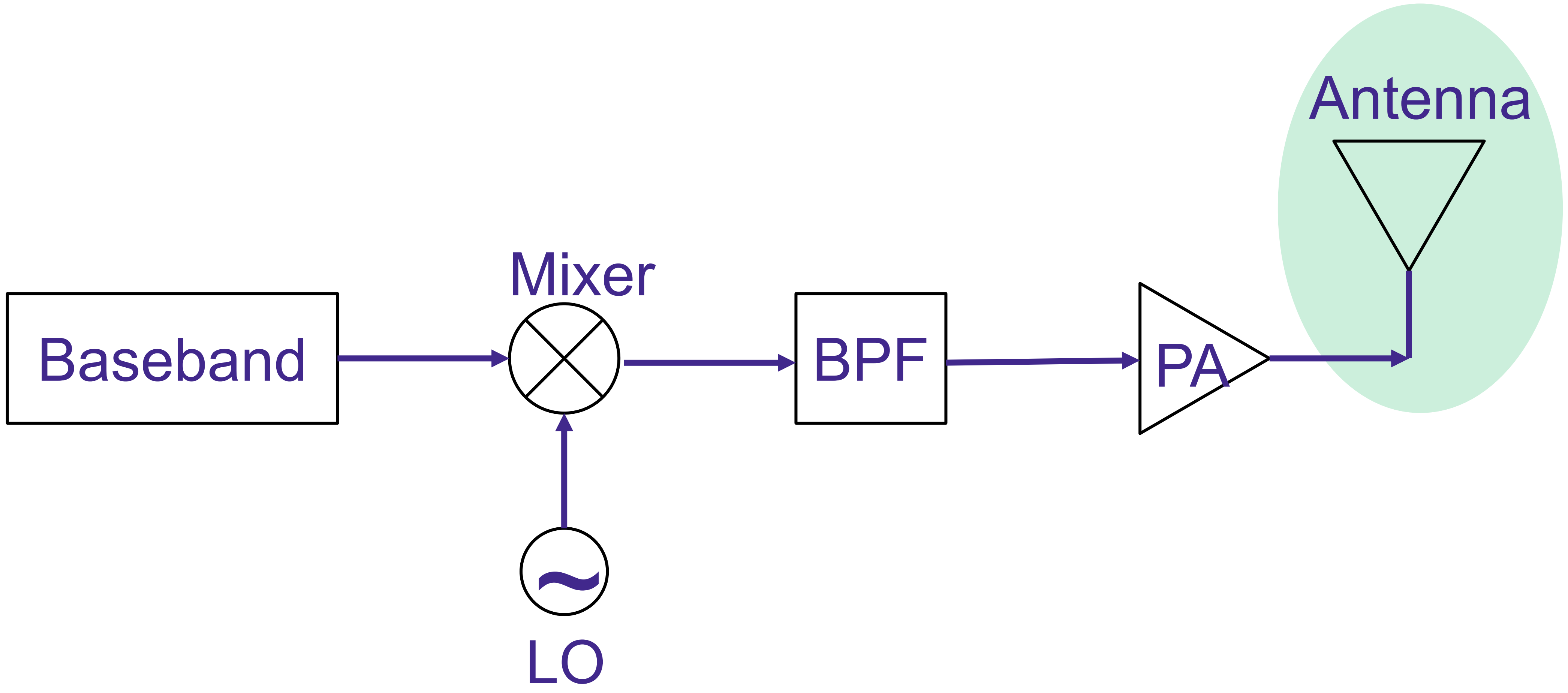


High power => go for low loss (minimized impact in usage)

Low power => go for simple (minimized impact in fab)

M. Wagih *et al.*, IEEE Journal of Microwaves, 2024

Some examples on antenna



Example: Reduction of materials

75% meshed

25% full for electrical contact with connector

Screen printing: Less wasted materials

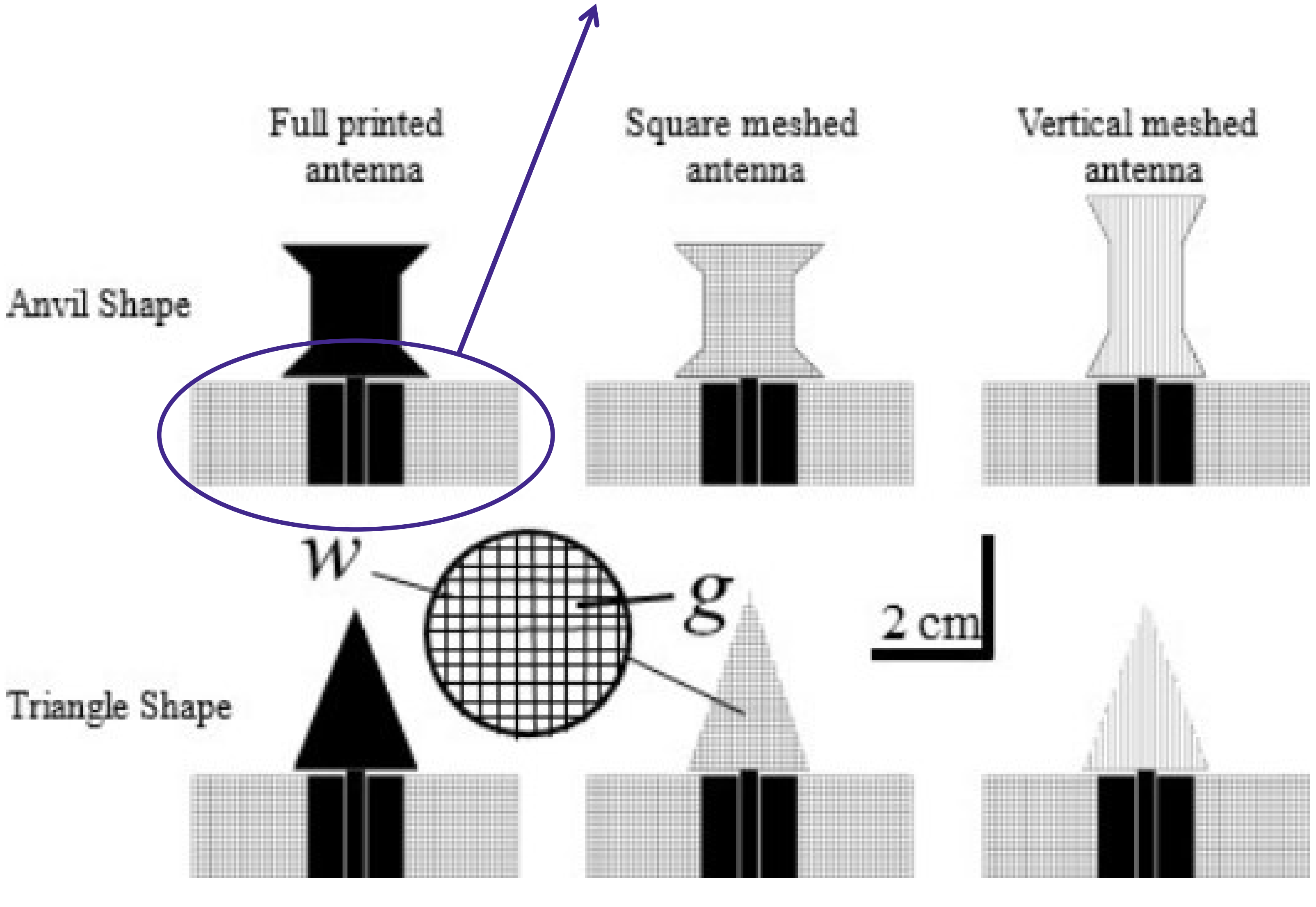
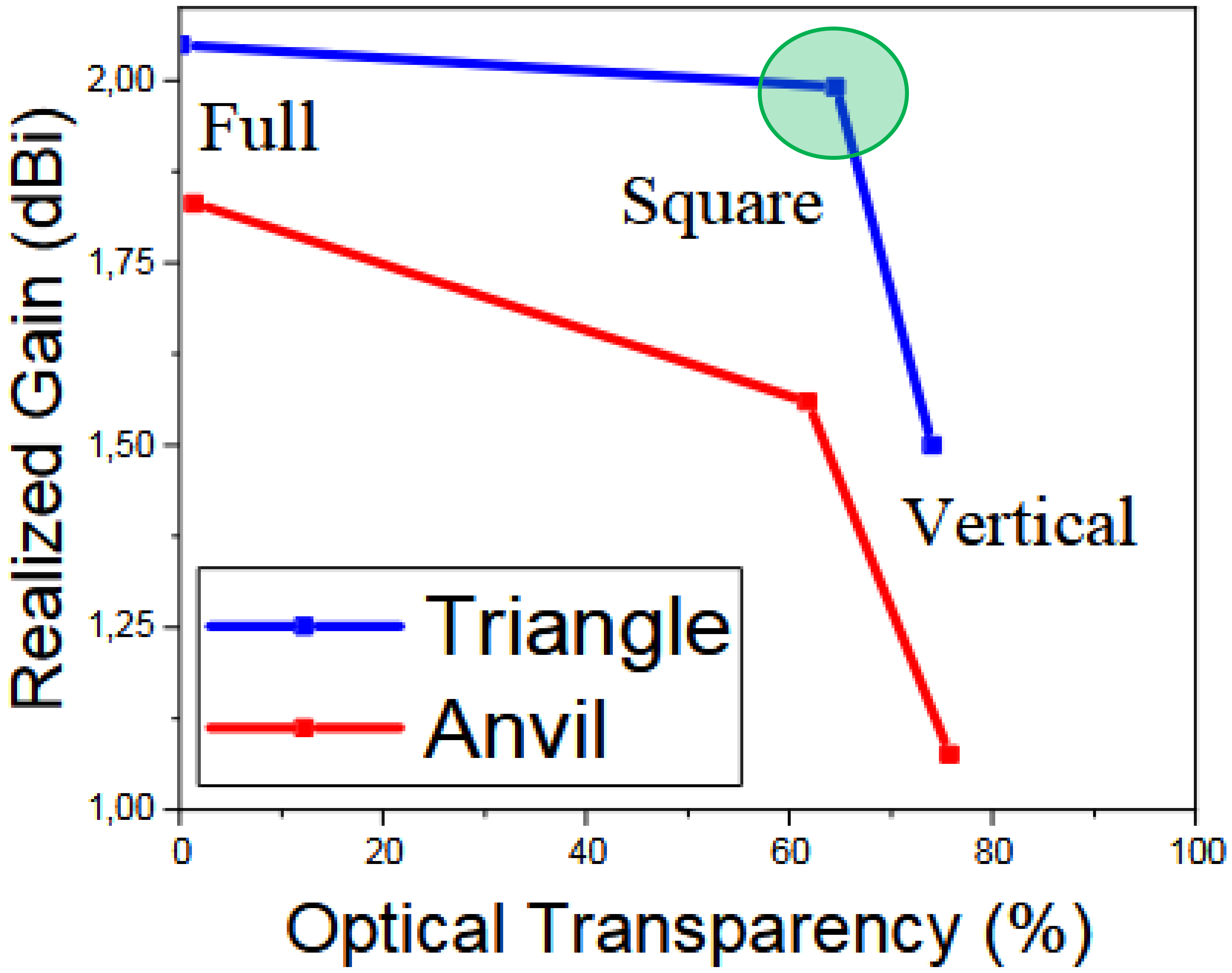


Fig. 2. Illustration of screen-printing

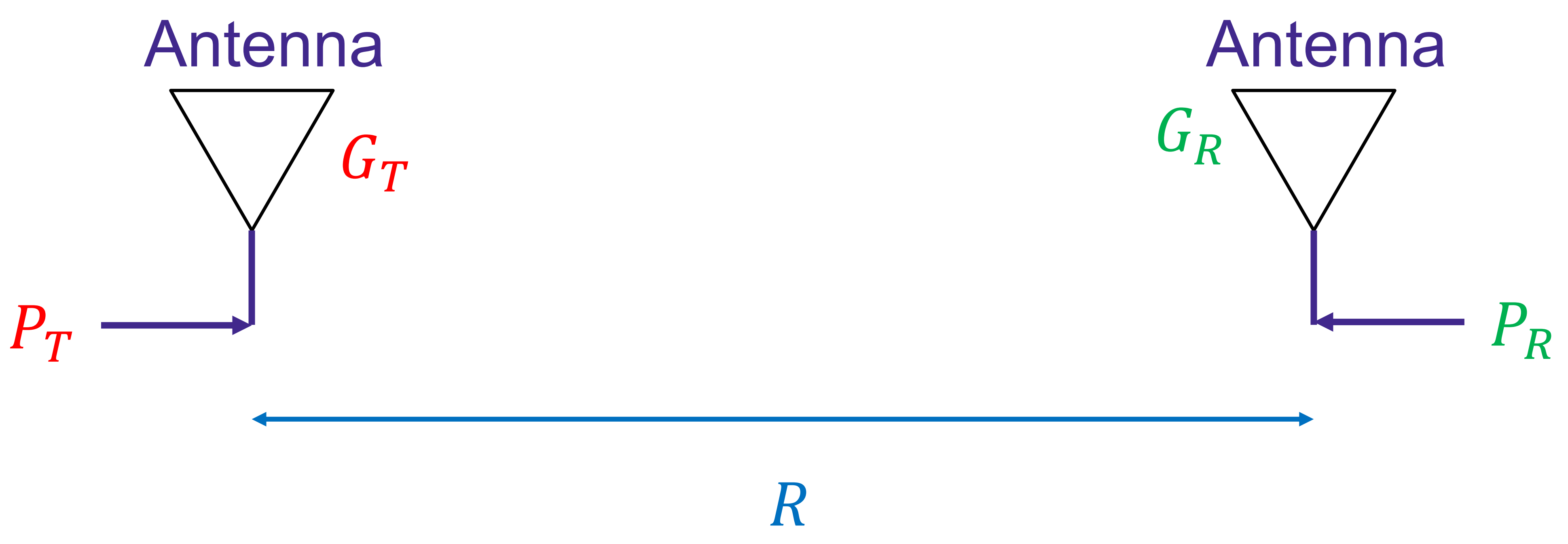


Monopole antenna @ 3.6 GHz

M. Wawrzyniak *et al.*, EuMW 2021

Example of a Figure-of-Merit (FoM) for antennas

FRIIS equation: $P_R = P_T \times G_T \times G_R \times \left(\frac{\lambda}{4\pi R}\right)^2$

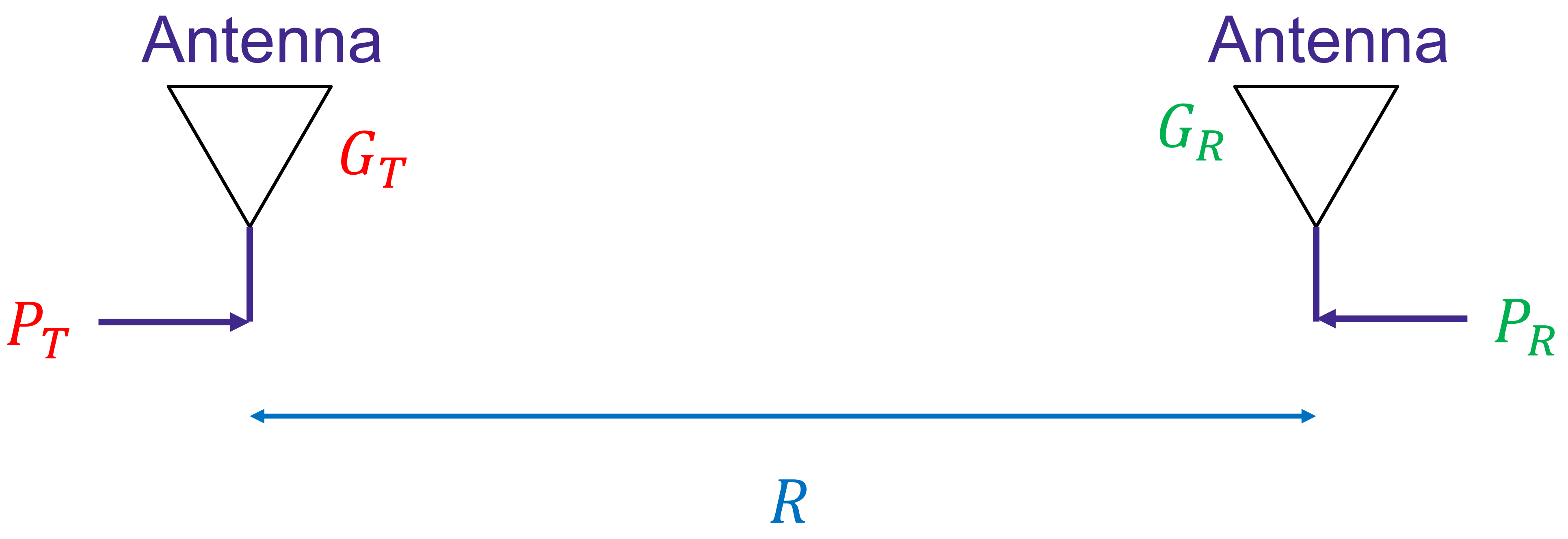


Where:

- P_R: Power at the receiving antenna
- P_T: Power delivered to transmitting antenna
- G_R: Gain of receiving antenna
- G_T: Gain of transmitting antenna
- λ: wavelength
- R: Distance between antennas

Example of a Figure-of-Merit (FoM) for antennas

FRIIS equation: $P_R = P_T \times G_T \times G_R \times \left(\frac{\lambda}{4\pi R}\right)^2$



For beamforming / directional

- Assuming same receiving antenna (G_R)
- Assuming same sensitivity (P_R)
- Assuming same distance (R)
- Assuming same frequency (λ)

=> $P_T \times G_T$ should hold constant

We want to minimize power consumption
=> P_T should be as small as possible
=> Looking for max G_T/P_T

We need to minimize metal quantity
=> Looking for minimum metal volume

$$FoM = \frac{G_T}{P_T} \times \frac{1}{V_{cu}}$$

Metal volume

Condition: Impact of dielectric << metal or same quantity of dielectric

Example: Reduction of materials

75% meshed

25% full for electrical contact with connector

$$FoM = \frac{G_T}{P_T} \times \frac{1}{Vmetal}$$

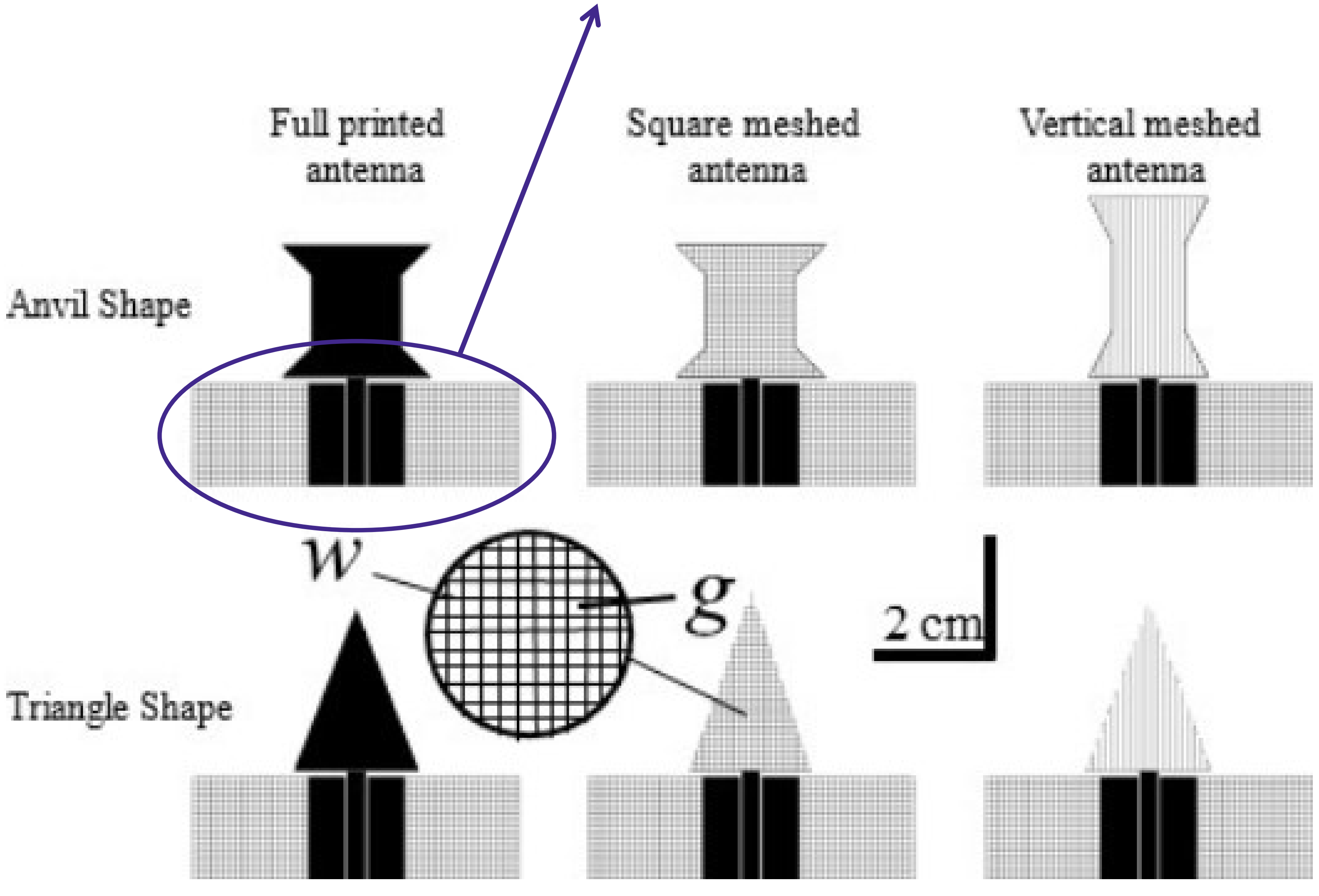
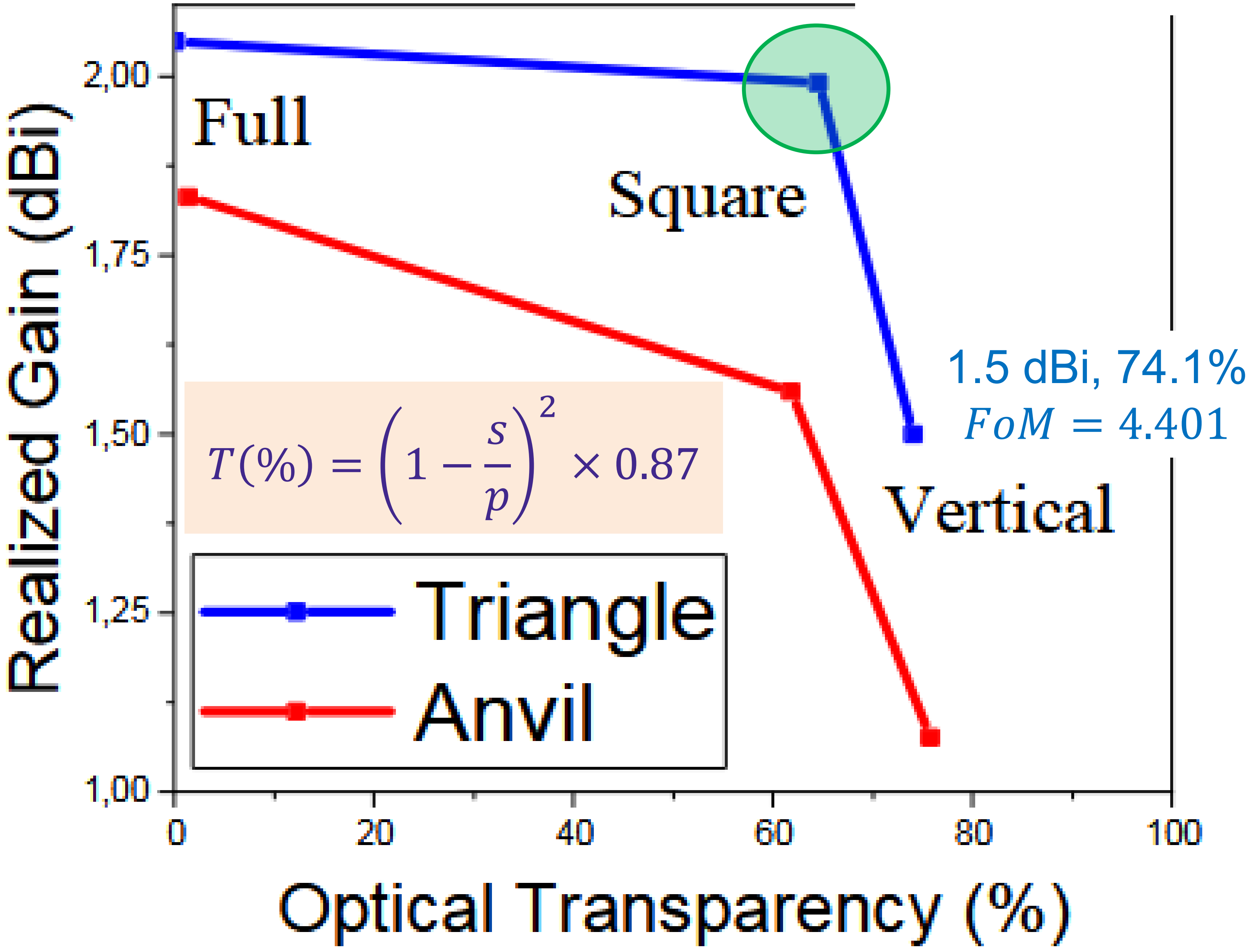


Fig. 2. Illustration of screen-printing

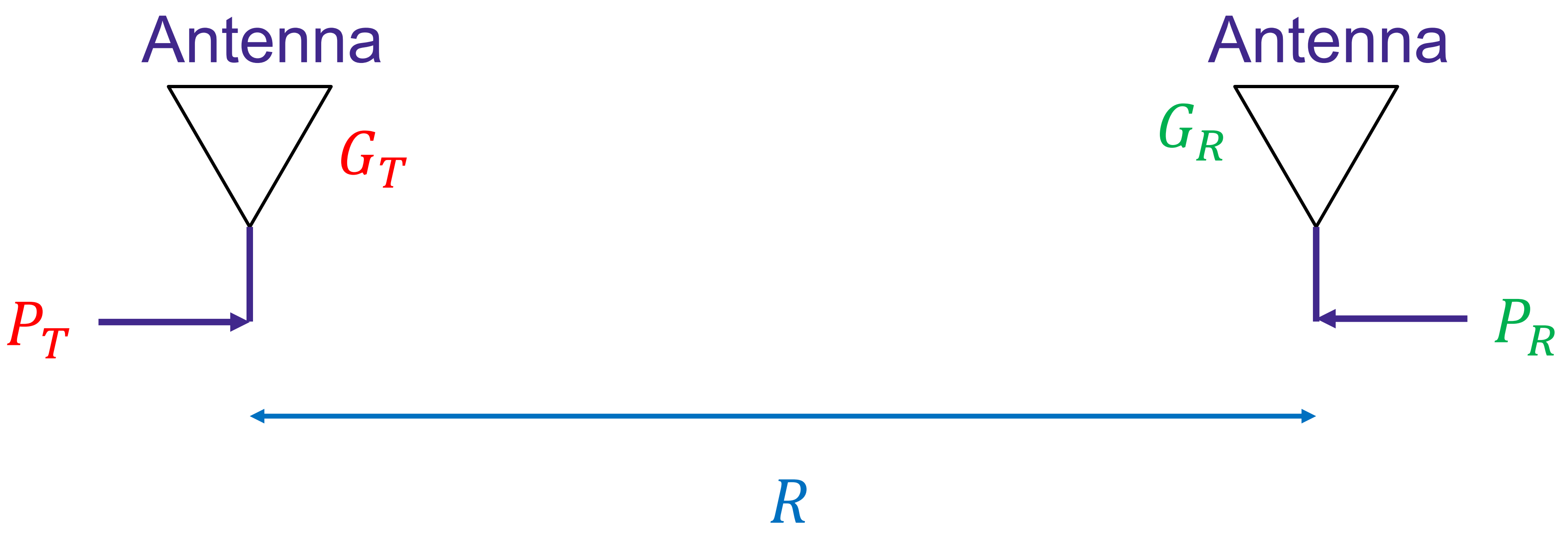


Monopole antenna @ 3.6 GHz

M. Wawrzyniak *et al.*, EuMW 2021

Example of a Figure-of-Merit (FoM) for antennas

FRIIS equation: $P_R = P_T \times G_T \times G_R \times \left(\frac{\lambda}{4\pi R}\right)^2$



For wide angle covering

- Assuming same receiving antenna (G_R)
- Assuming same sensitivity (P_R)
- Assuming same distance (R)
- Assuming same frequency (λ)
- Same covering angle θ

=> $P_T \times G_T$ should hold constant

We want to minimize power consumption
=> P_T should be as small as possible
=> Looking for max G_T/P_T

We need to minimize metal quantity
=> Looking for minimum metal volume

$$FoM = \frac{G_T}{P_T} \times \frac{1}{V_{cu}} \times \frac{\theta}{HPBW}$$

Condition: Impact of dielectric << metal or same quantity of dielectric

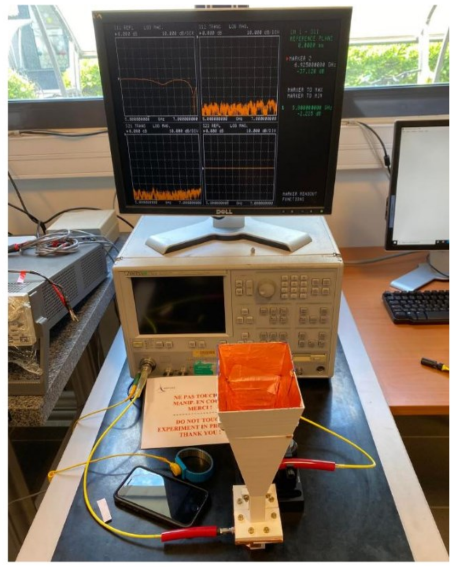
Other approaches

Long lifetime / reusable:

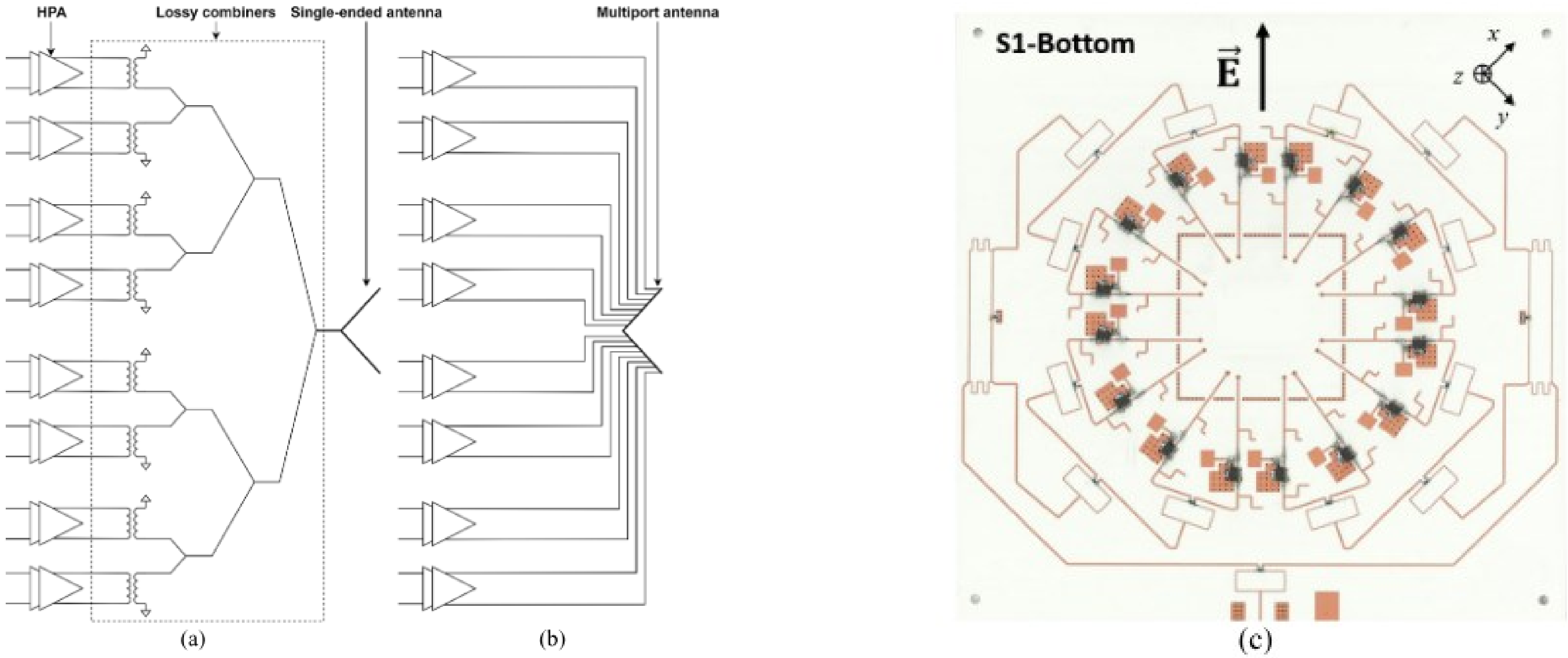
Surface mounted horn antenna

Yagi Uda antenna

Multifunctional:



Modular

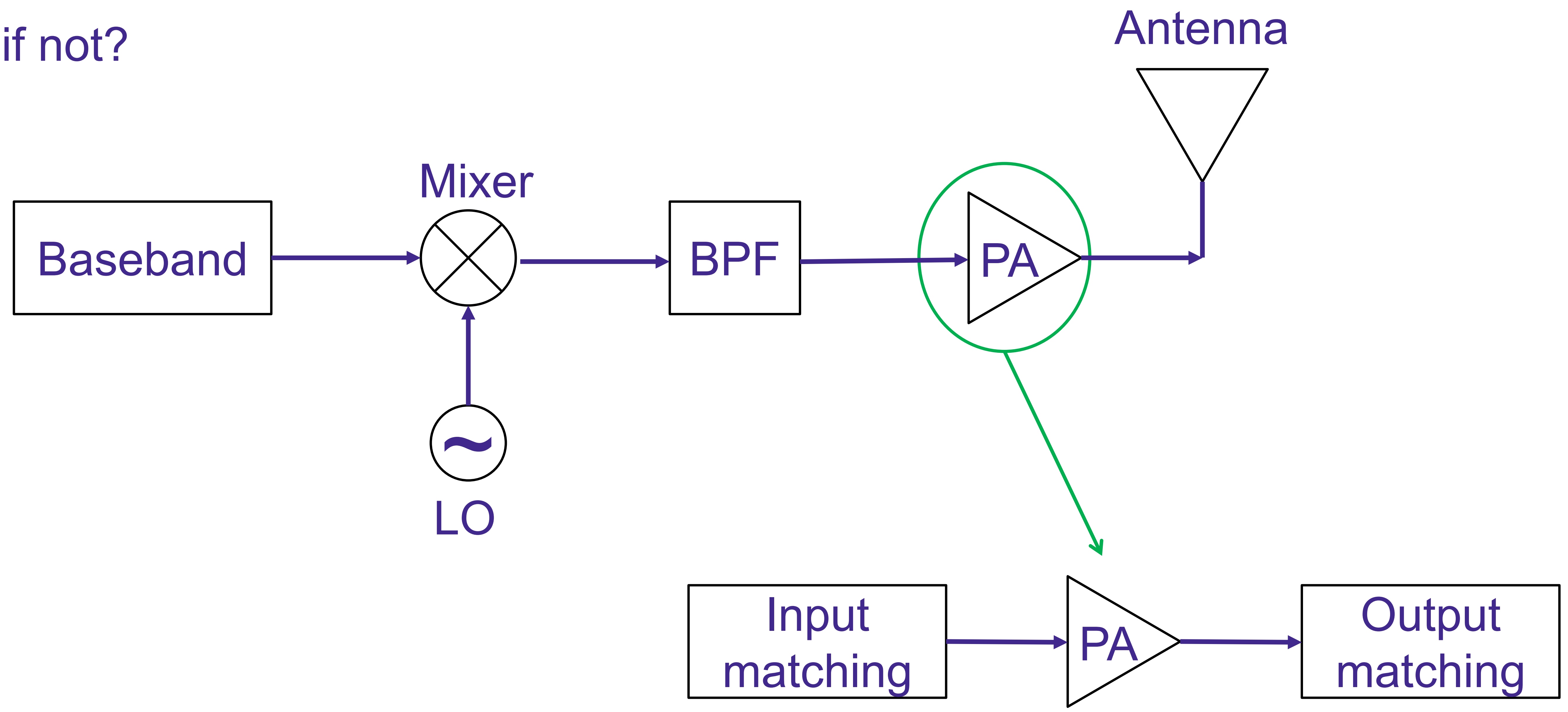


On antenna power combining
T. Le Gall *et al.*, IEEE TAP 2024

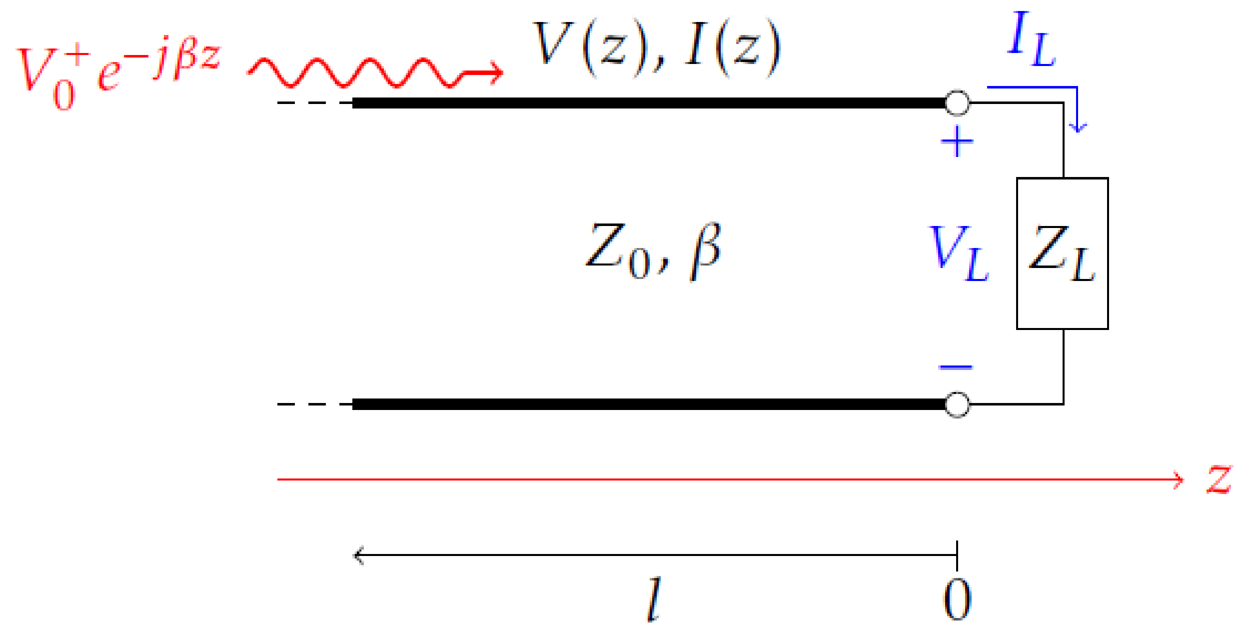
Example on the “refuse” of matching network

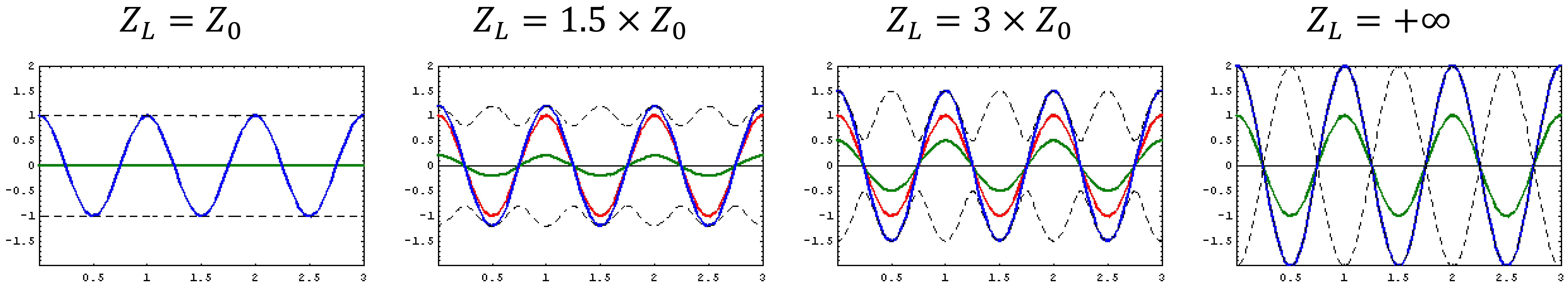
If all components are “standardized” to 50 Ω => ☺

What happens if not?



The need of matching network

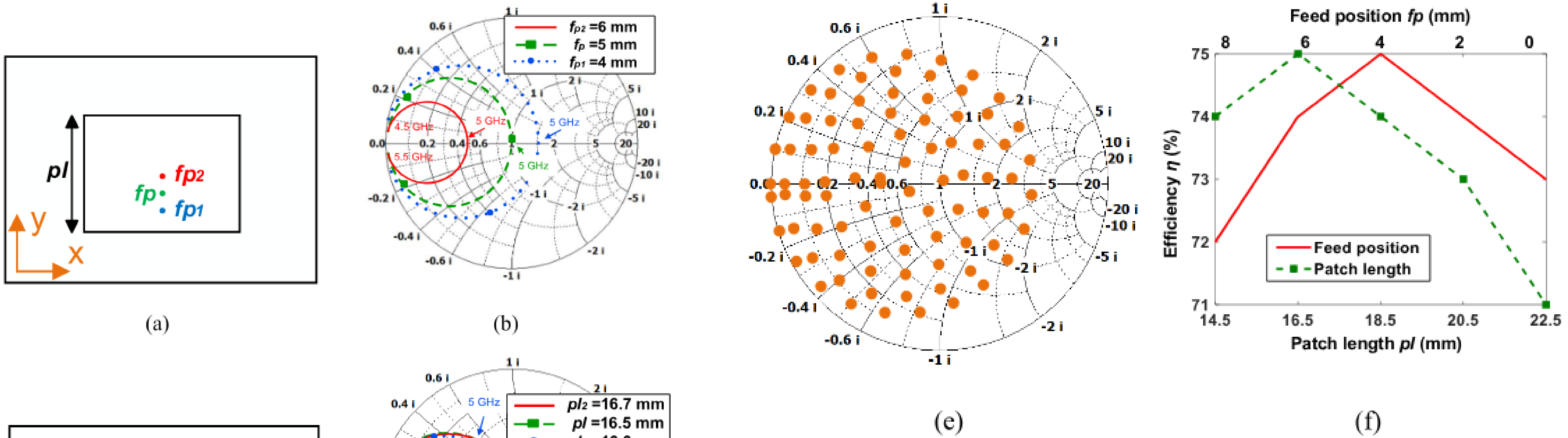


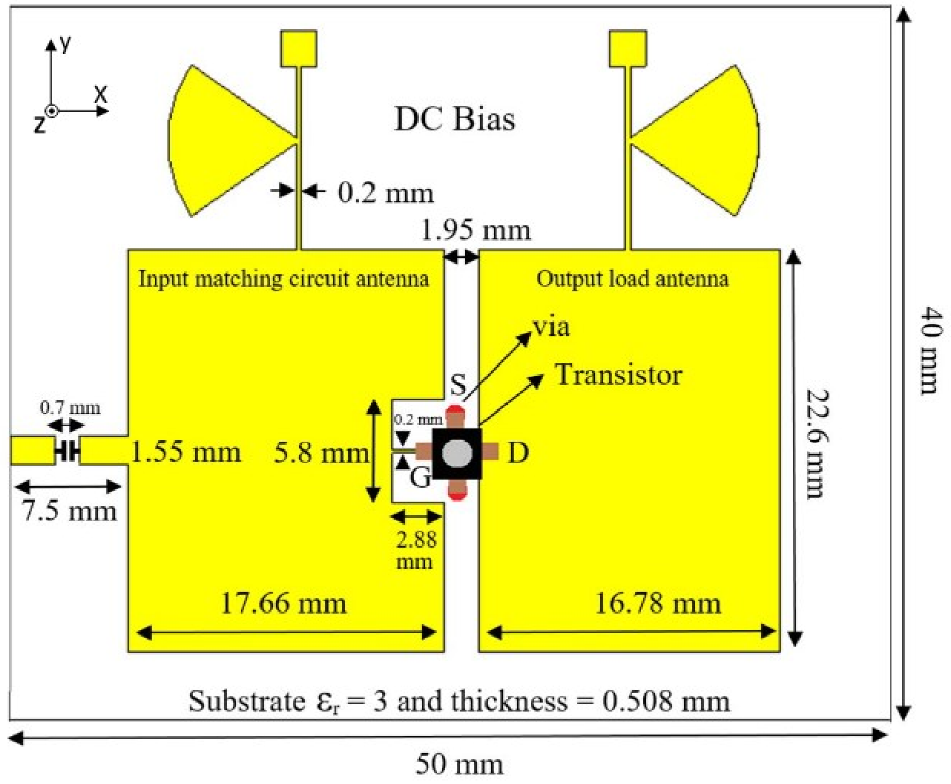


— Incident wave — Reflected wave — Standing wave

1D standing wave (takuichi.net)

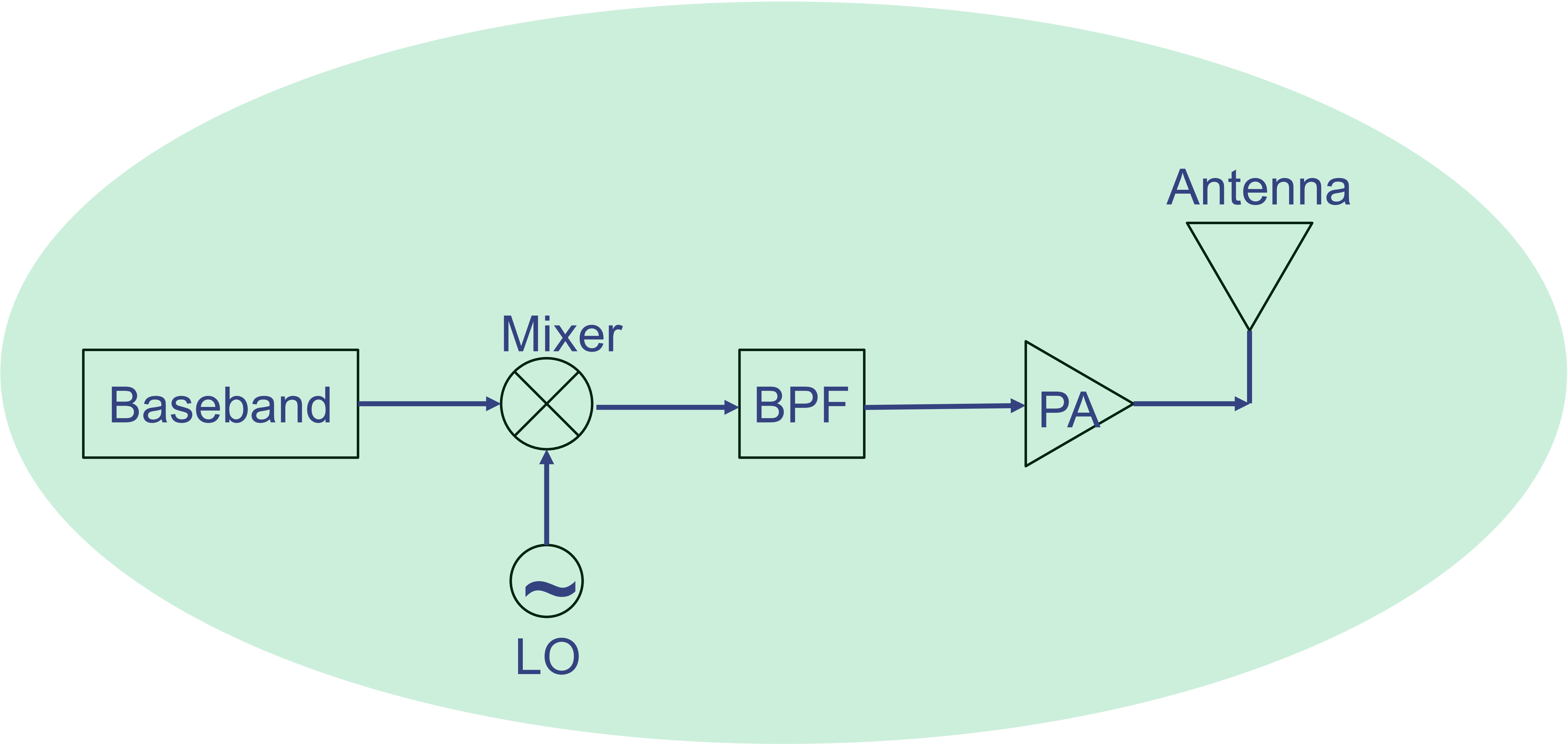
Self-adapted design





S. N. Nallandhigal and K. Wu, IEEE T-MTT 2019

Example on substrates



Reusable

Table 3. Scenarios used for LCA of the FR-4 and Steel-based PVs.

Control 1	FR-4, all components to landfill
Control 2	FR-4, components recovered, substrate incinerated
Scenario 1	Steel all components to landfill
Scenario 2	90% of steel recycled. All components to landfill
Scenario 3	90% of steel recycled. 100% of ICs, capacitors, and resistors are recycled

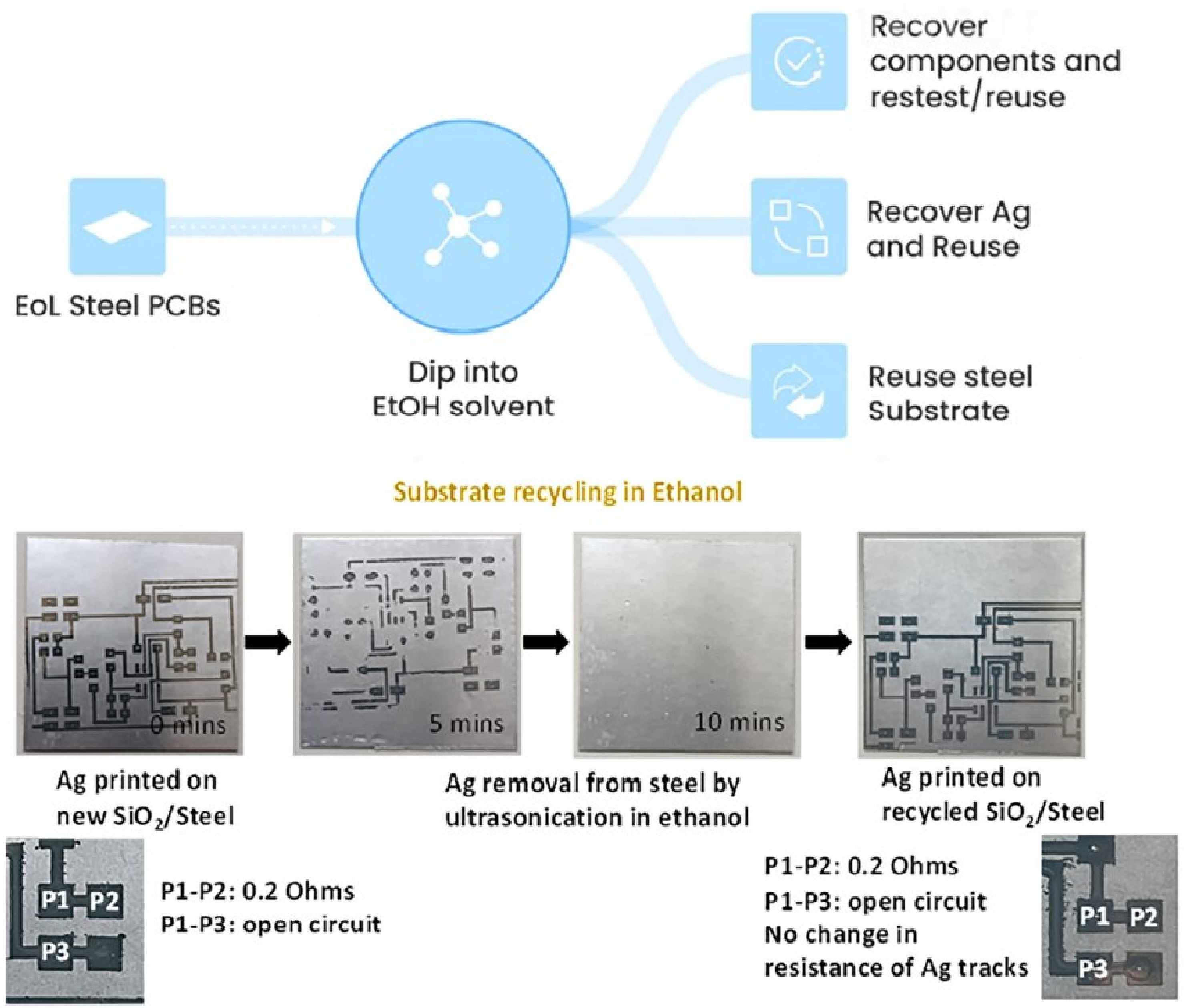
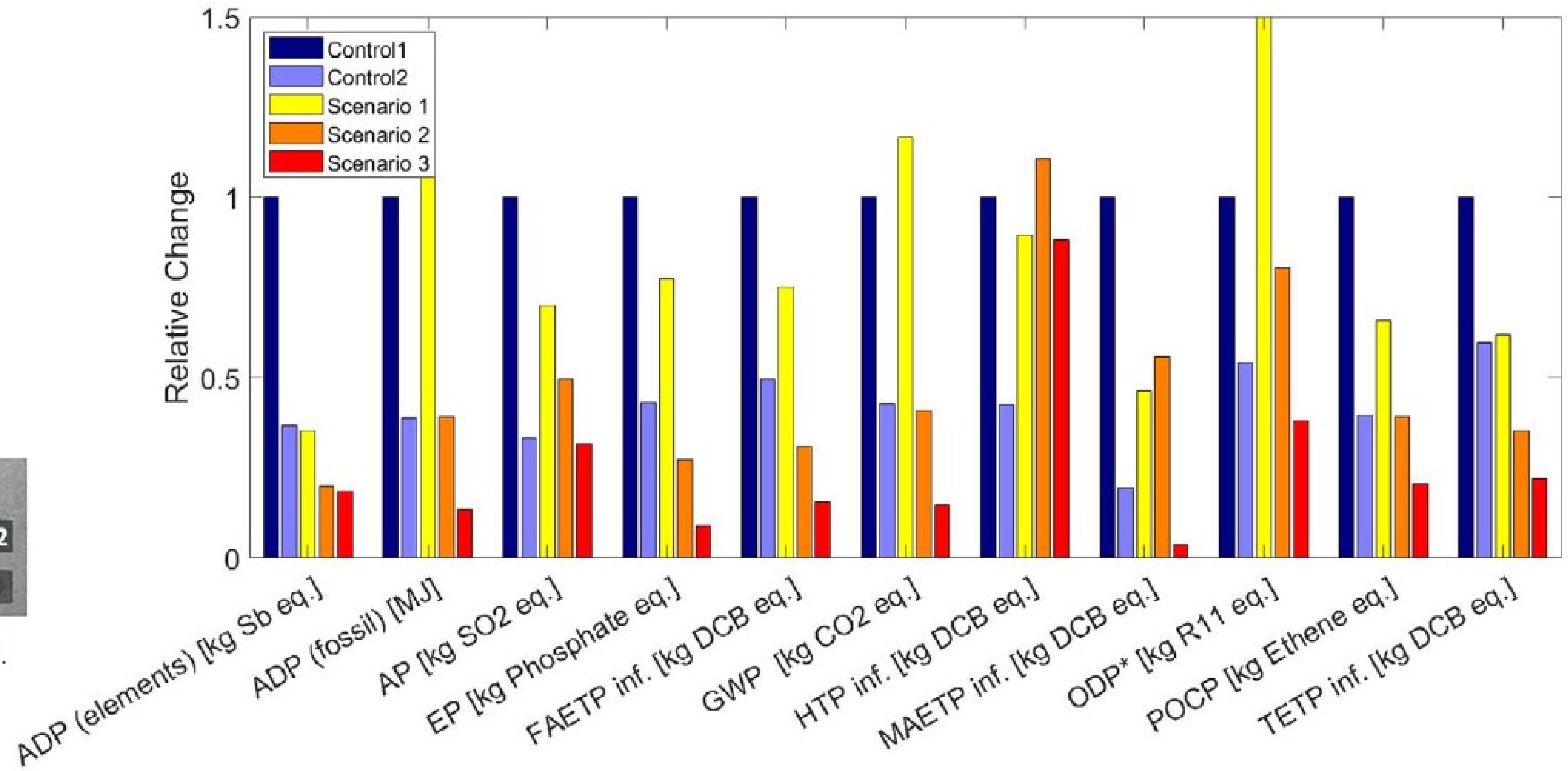
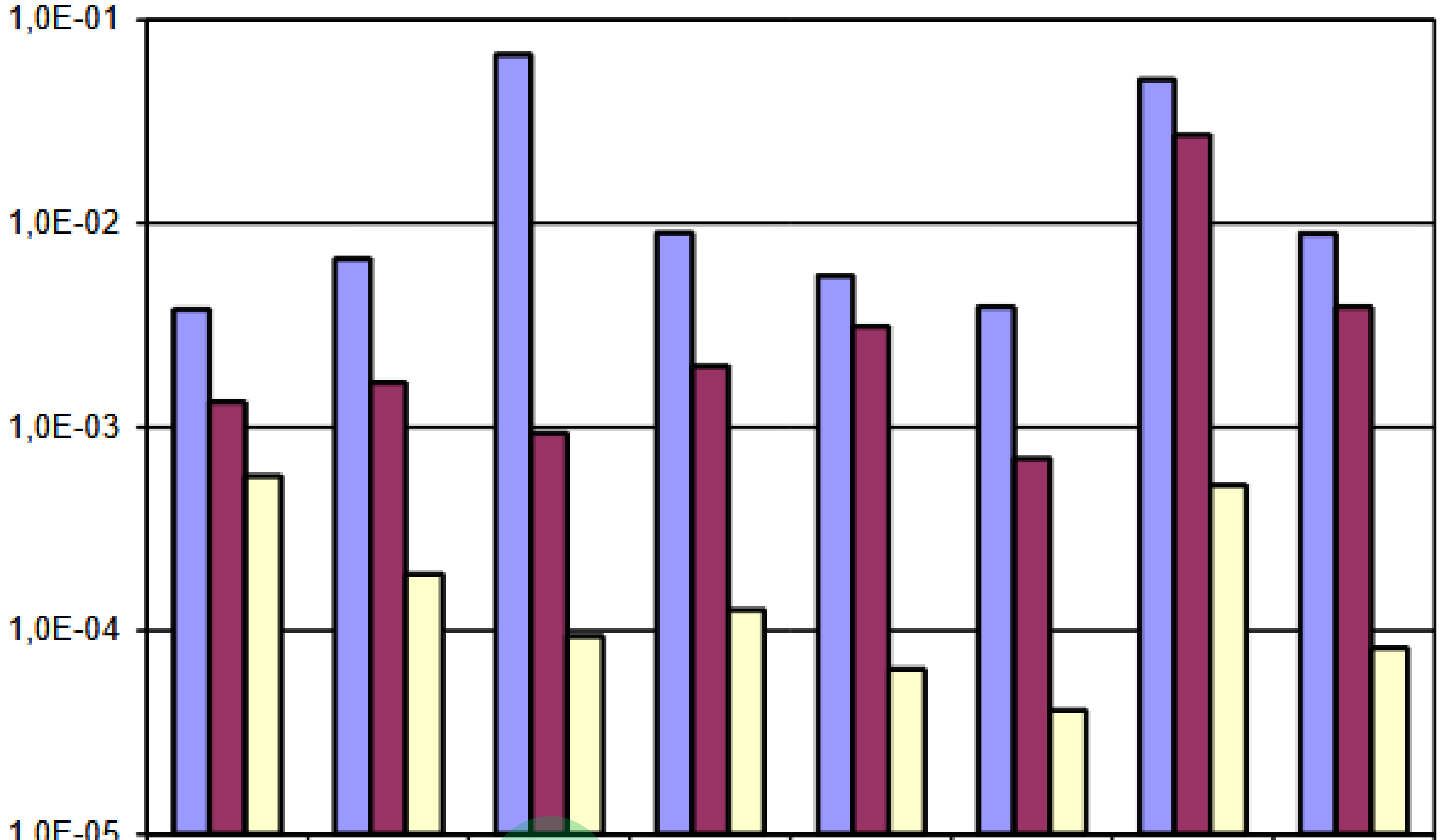


Figure 5. a) Concept used for recycling steel-based PCBs and b) Recycling of SiO_x /steel substrates by ultrasonication in EtOH.



J. Kettle *et al.*, Advanced Electronic Materials, 2025

Bio-sourced substrates



	Energy NR (MJ eq)	Ressources (kg Sb eq)	GWP 100 mod (kg CO2 eq)	Acidification (kg SO2 eq)	Eutrophis. (kg PO4-eq)	Photochemical poll. (kg C2H4)	Ecotoxicity (kg 1,4-DB eq)	Human toxicity (kg 1,4-DB eq)
Rogers	3,8E-03	6,7E-03	6,7E-02	9,0E-03	5,5E-03	3,9E-03	5,1E-02	8,9E-03
PLA	1,3E-03	1,7E-03	9,3E-04	2,0E-03	3,1E-03	7,0E-04	2,7E-02	3,9E-03
Paper	5,8E-04	1,9E-04	9,4E-05	1,3E-04	6,5E-05	4,1E-05	5,1E-04	8,2E-05

- Three antennas for 5.5 GHz Wifi
- Bilan Produit from ADEME

Example:

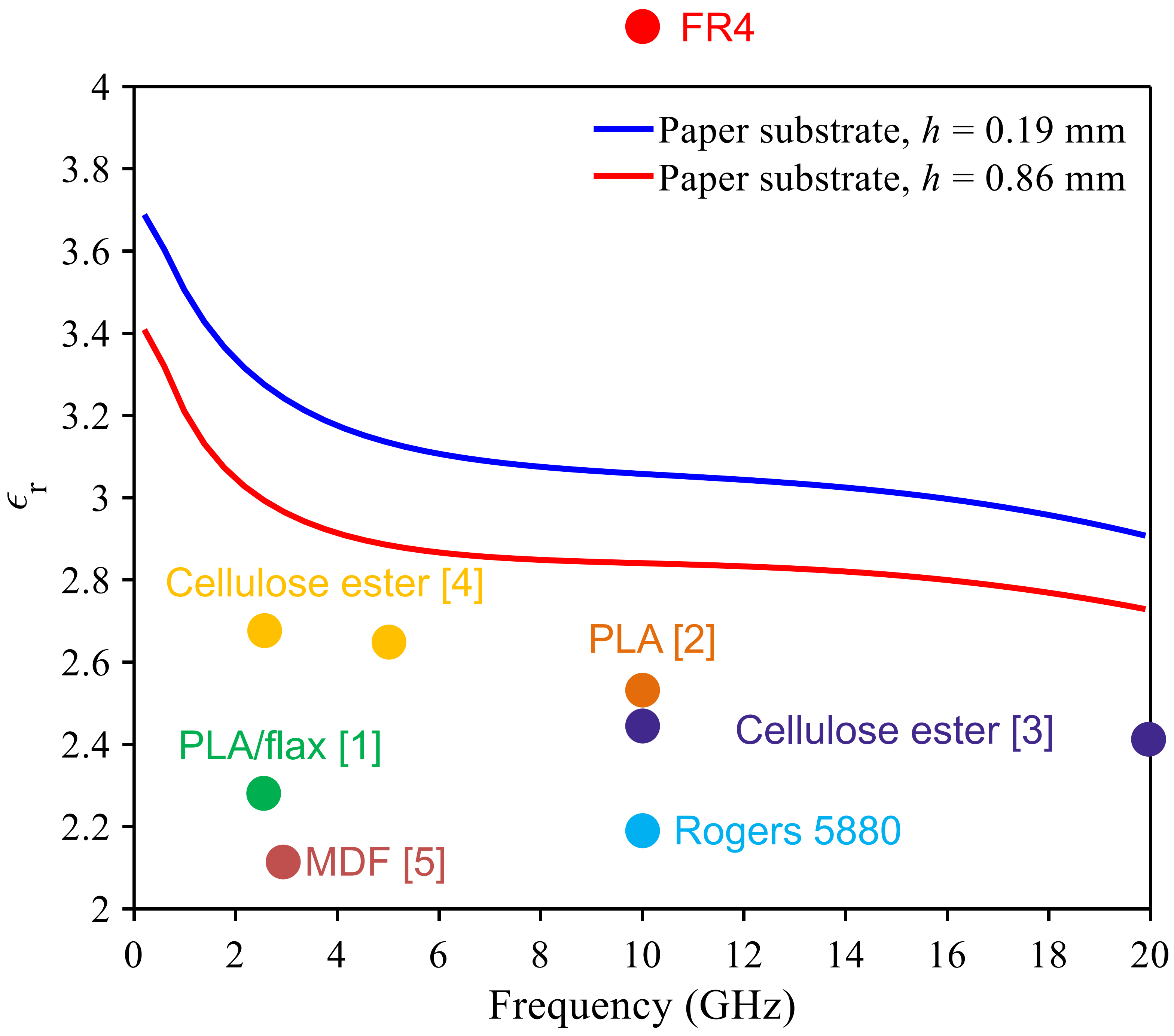
GWP 100 mod (kg CO2 eq):
Rogers ~ 72 × PLA
Rogers ~ 712 × paper substrate

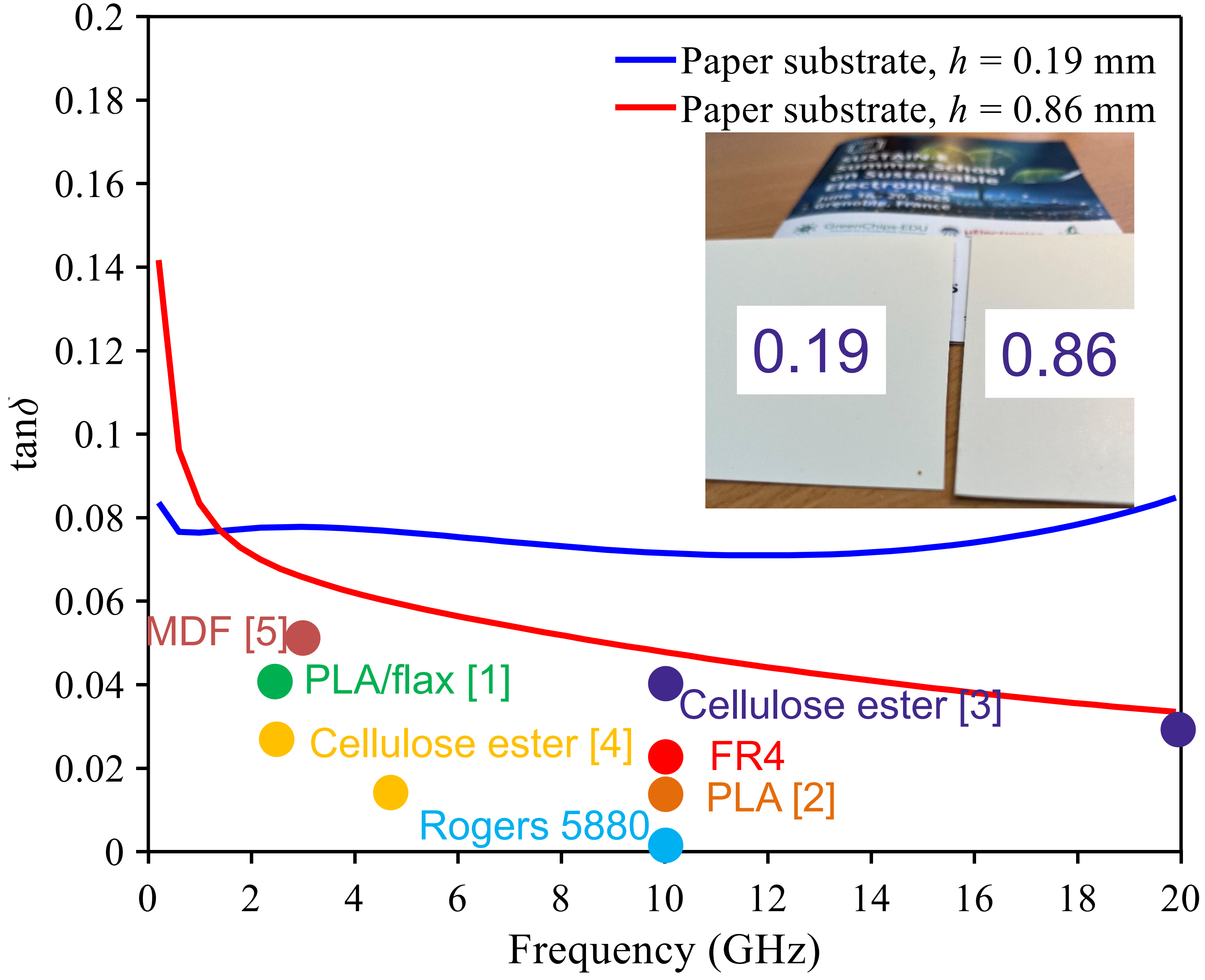
Bio-based materials
could be potential candidates

P. Xavier and T. P. Vuong, IEEE LAEDC, 2022

Some bio-sourced substrates

Special thanks to Arnaud Vena & Georges Chehade @ IES Univ. Montpelier for wideband characterization of paper substrates

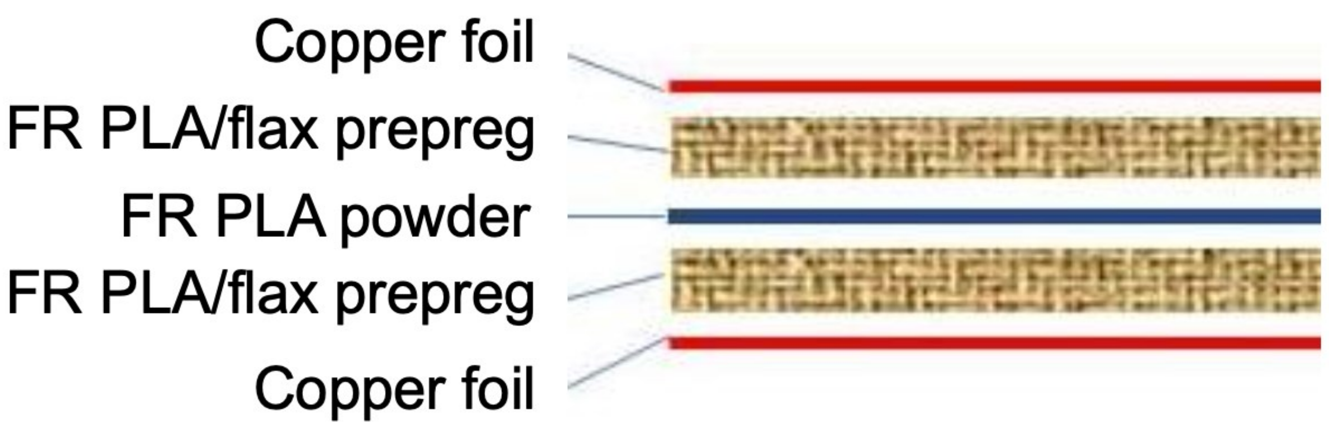




[1] – V. Grennerat *et al.*, IEEE EuCAP 2024
[2] – G. Boussatour *et al.*, IEEE MWCL 2018
[3] – P-Y. Cresson *et al.*, IEEE TMTT 2020
[4] – A. Sid *et al.*, IEEE EuMW 2024
[5] – C. Bourretere *et al.*, EuMW 2024

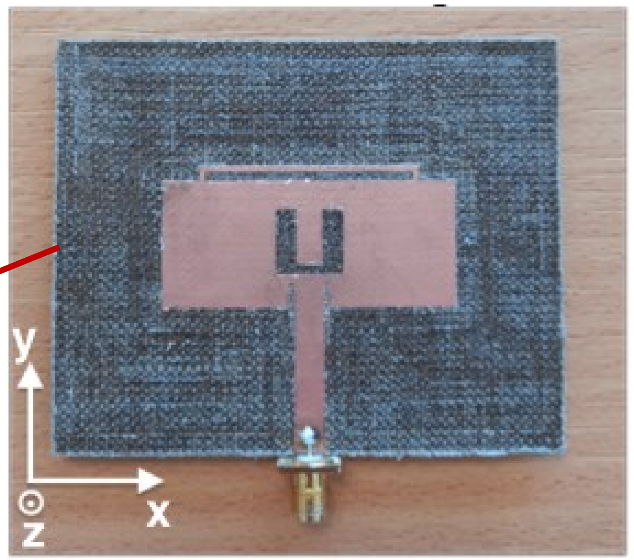
Bio-based substrates are more lossy than high performance Rogers substrates
But can be comparable with FR-4

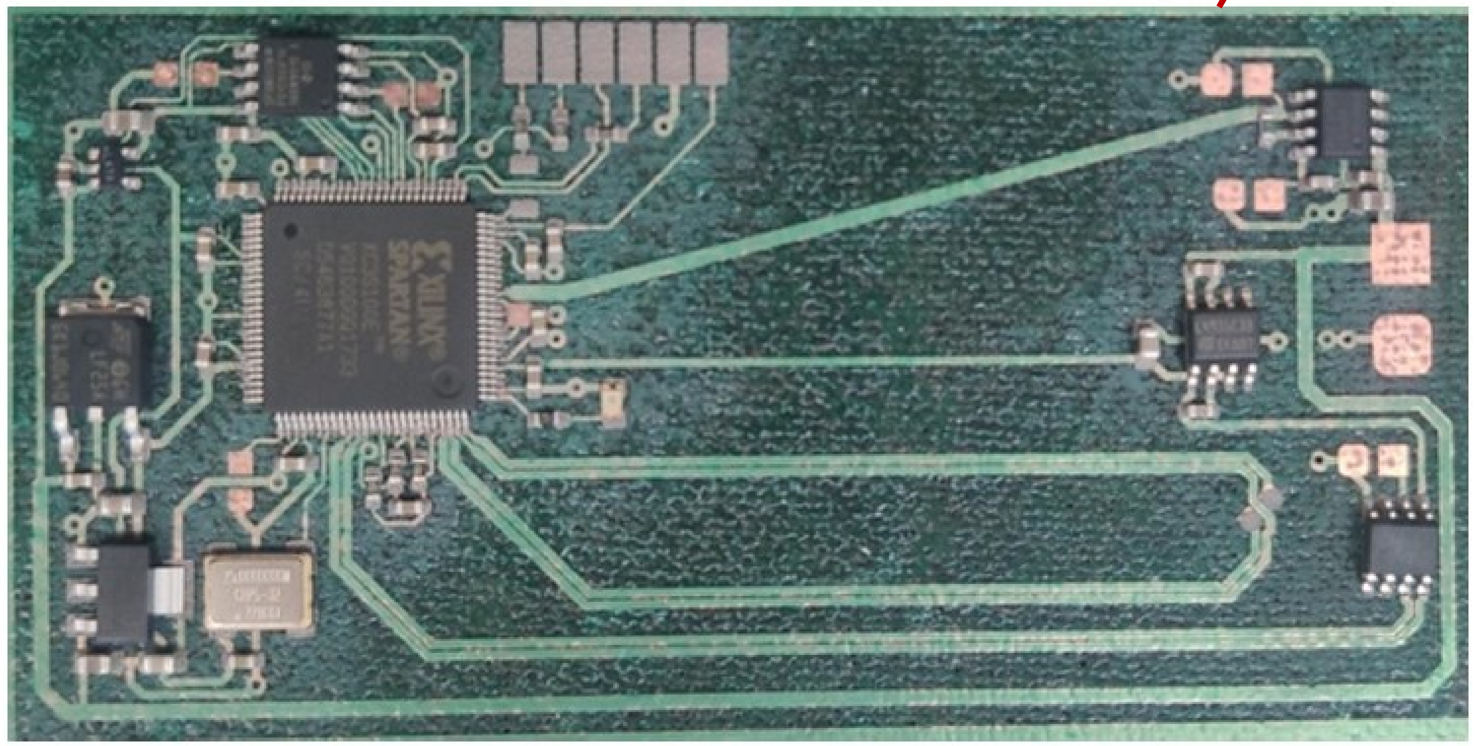
Some examples – Bio-sourced materials – PLA/flax



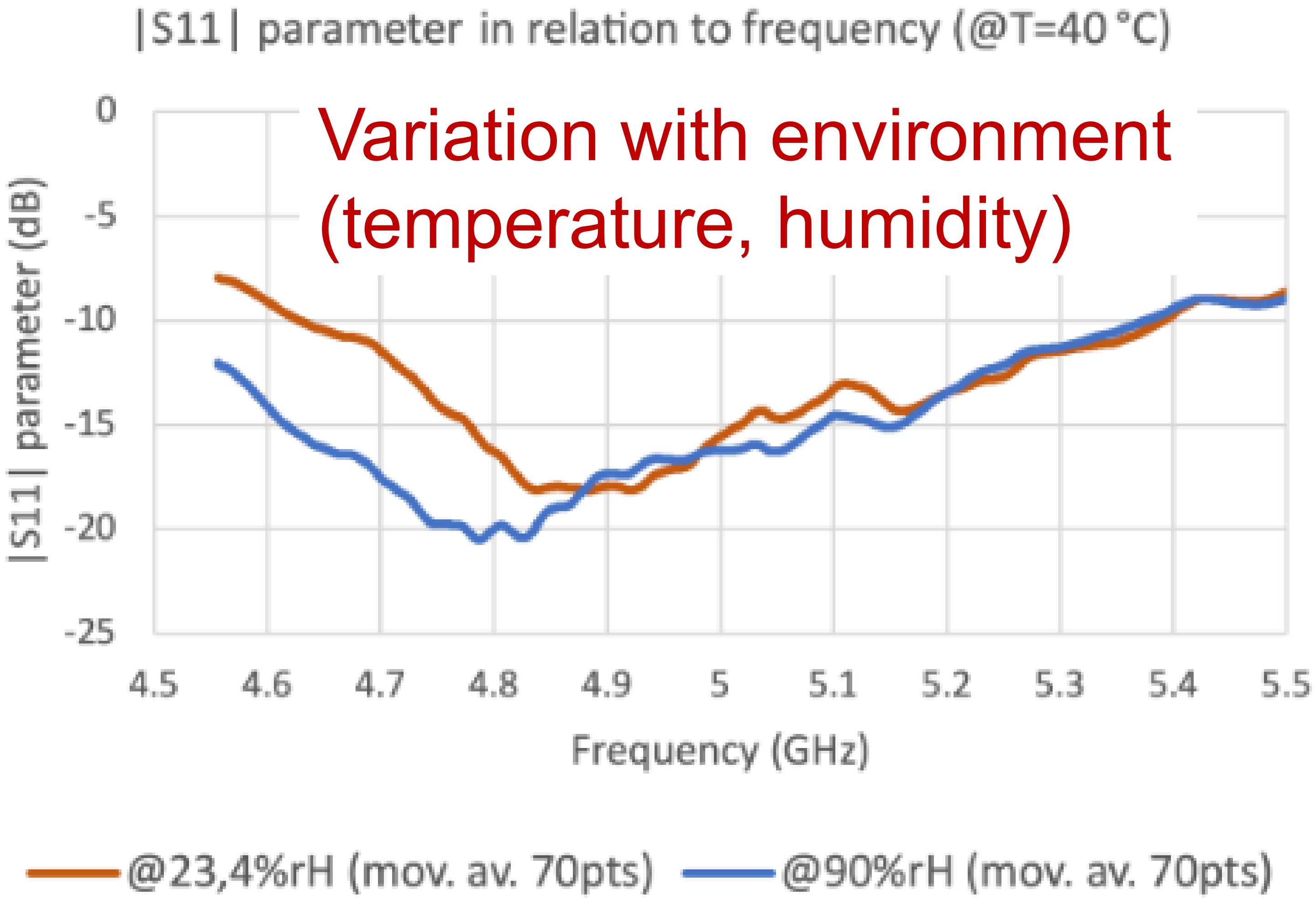
PLA / flax fiber from MESHLIN
V. Grennerat *et al.*, MiNaPAD 2024

Surface roughness
(flax fiber)





V. Grennerat *et al.*, ISSE 2023



Variation with environment
(temperature, humidity)

V. Grennerat *et al.*, EuCAP 2024

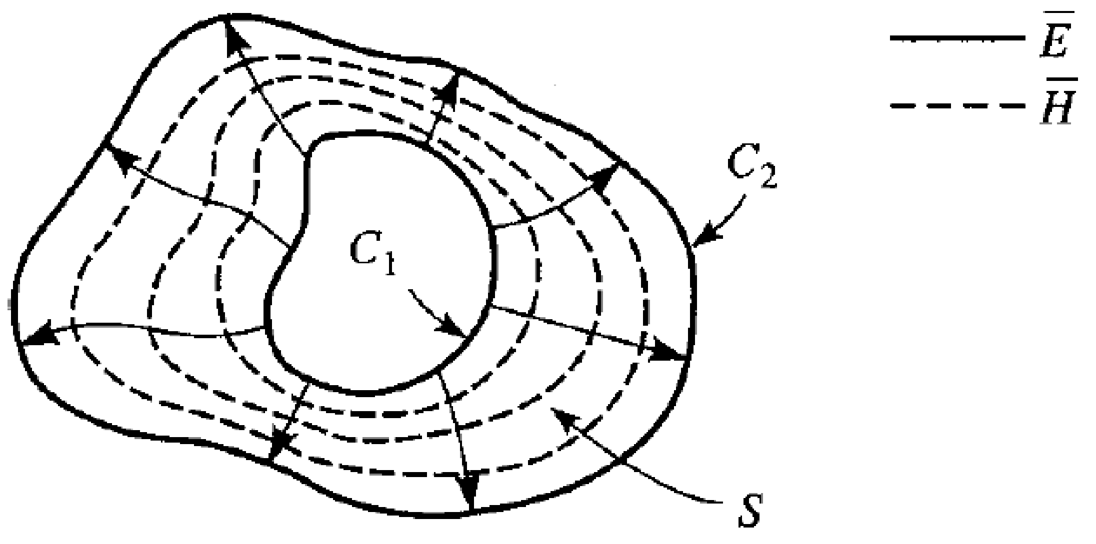
Effect of surface roughness

$$R = \frac{R_s}{|I_o|^2} \int_{C_1+C_2} \bar{H} \cdot \bar{H}^* dl \ \Omega/\text{m}.$$

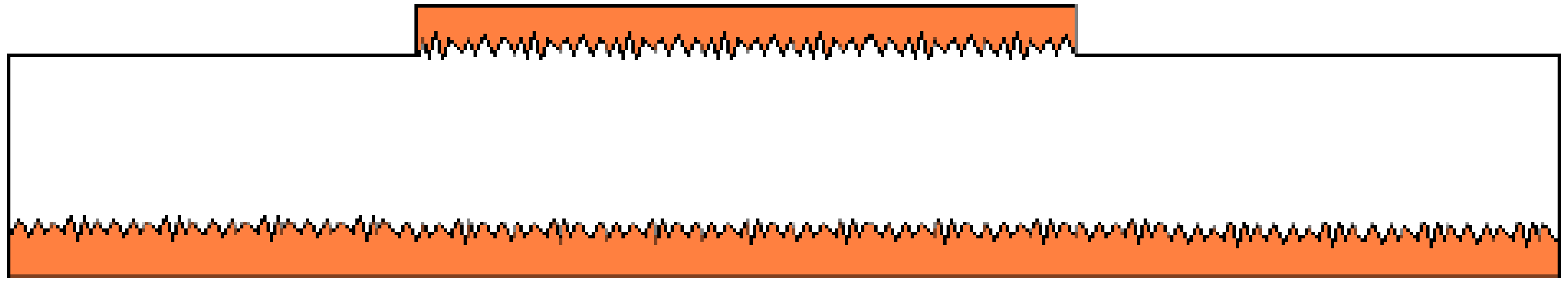
Surface resistance: $R_s = \sqrt{\frac{\omega\mu}{2\sigma}} = \frac{1}{\sigma\delta_s}$

Skin depth: $\delta_s = \sqrt{\frac{2}{\omega\mu\sigma}}$

Field lines on an arbitrary TEM transmission line



Rs depends on:
- Conductivity σ
- Frequency ω
- Surface roughness Δ



Surface roughness (Δ) $R_s' = R_s \times K_{SR} = R_s \times \left[1 + \frac{2}{\pi} \times \text{atan}\left(1.4\left(\frac{\Delta}{\delta_s}\right)^2\right)\right]$ => Increase surface impedance => More loss

Tao Liang *et al.*, IEEE IMS 2006

Effect of surface roughness

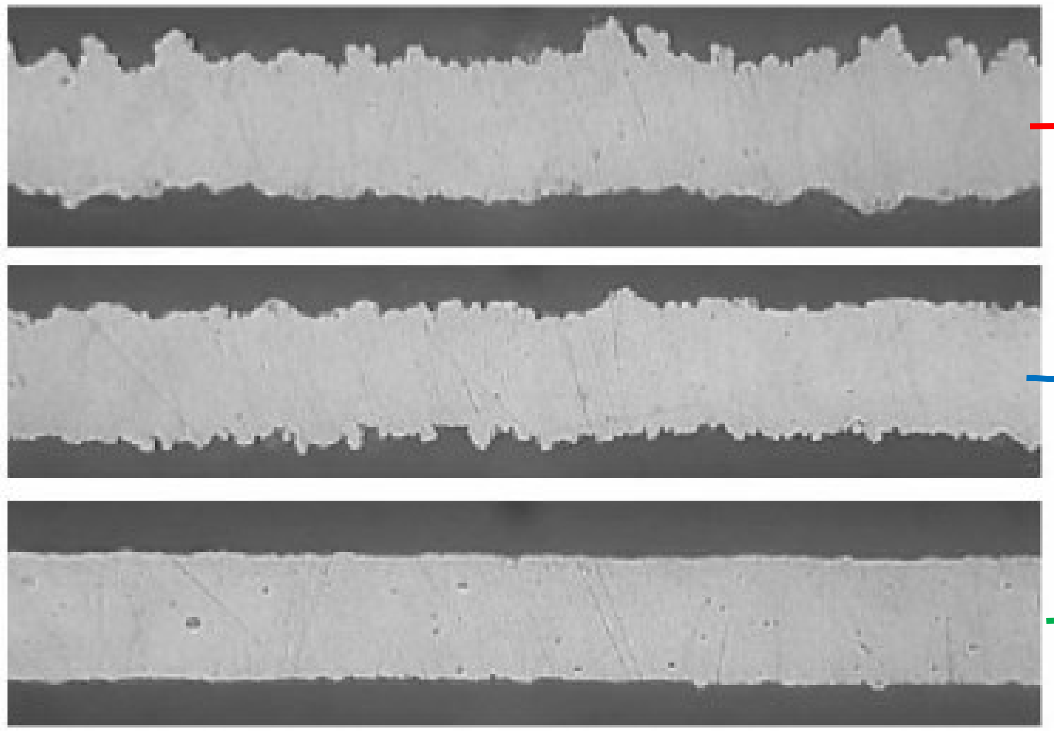


Fig. 1. Cross section of typical copper foils: surface trace (top), internal trace (middle), and near-smooth copper (bottom)

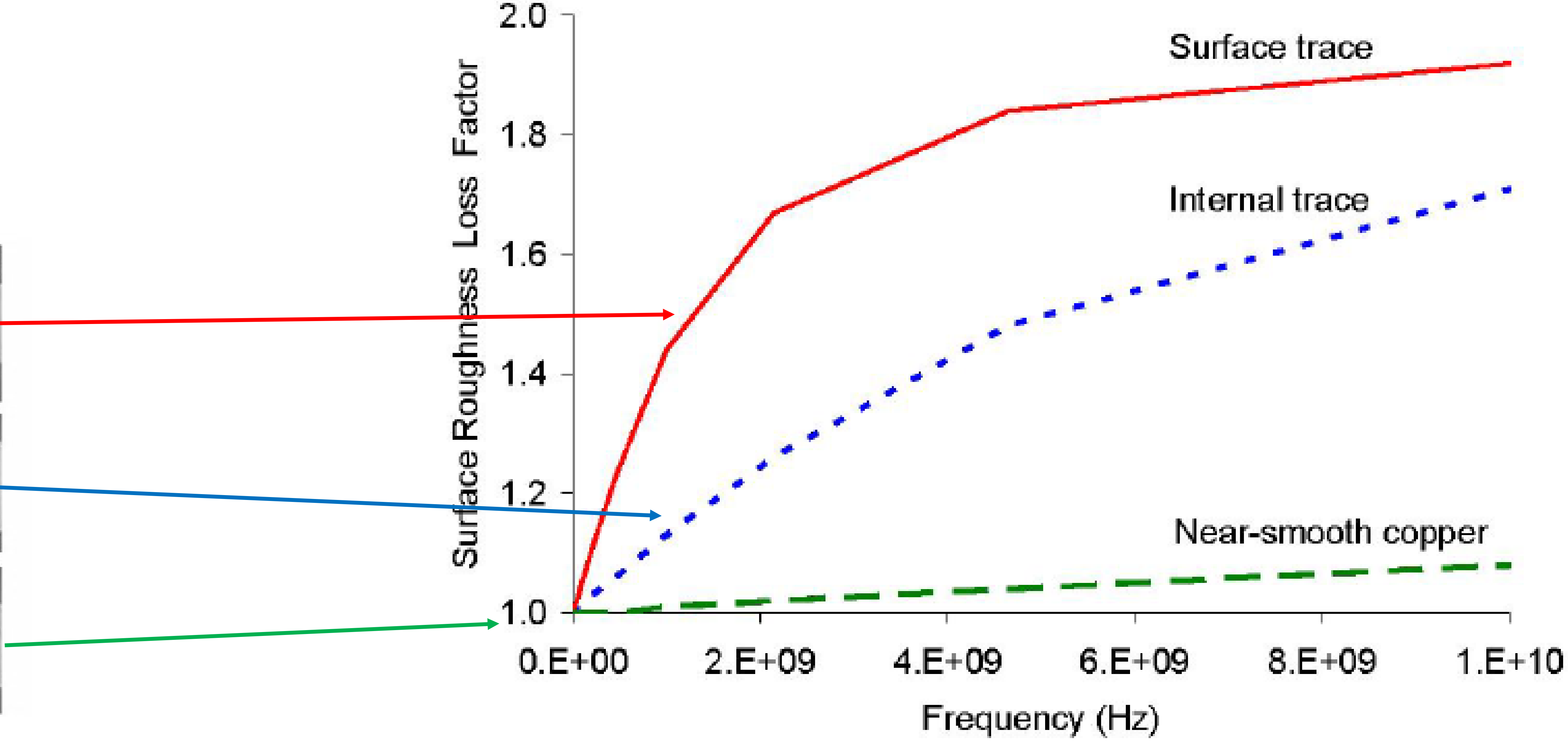


Fig. 2. Loss factor K_{sr} due to surface roughness effect

Tao Liang *et al.*, IEEE IMS 2006

Effect of surface roughness

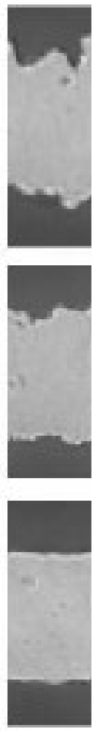
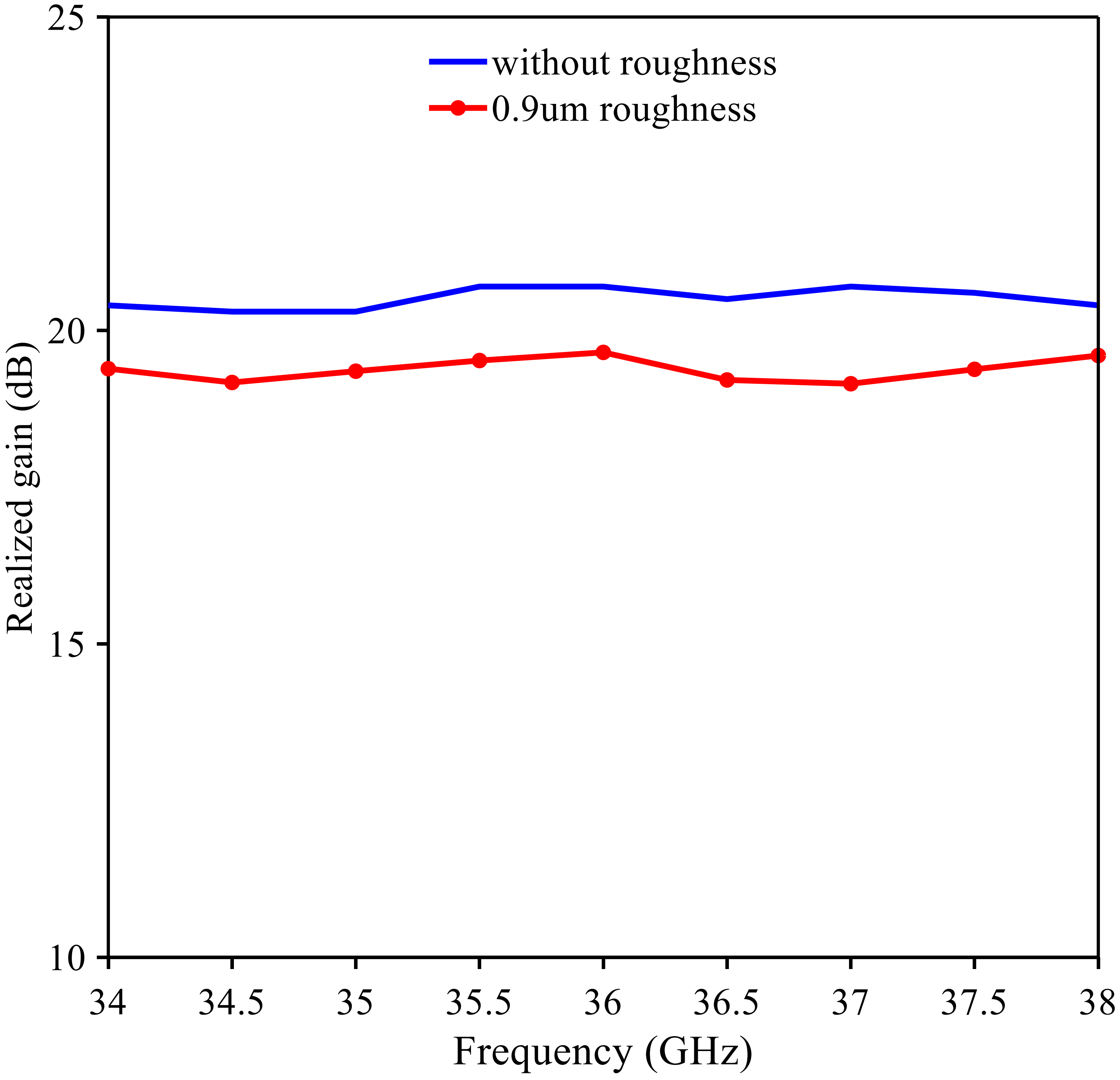
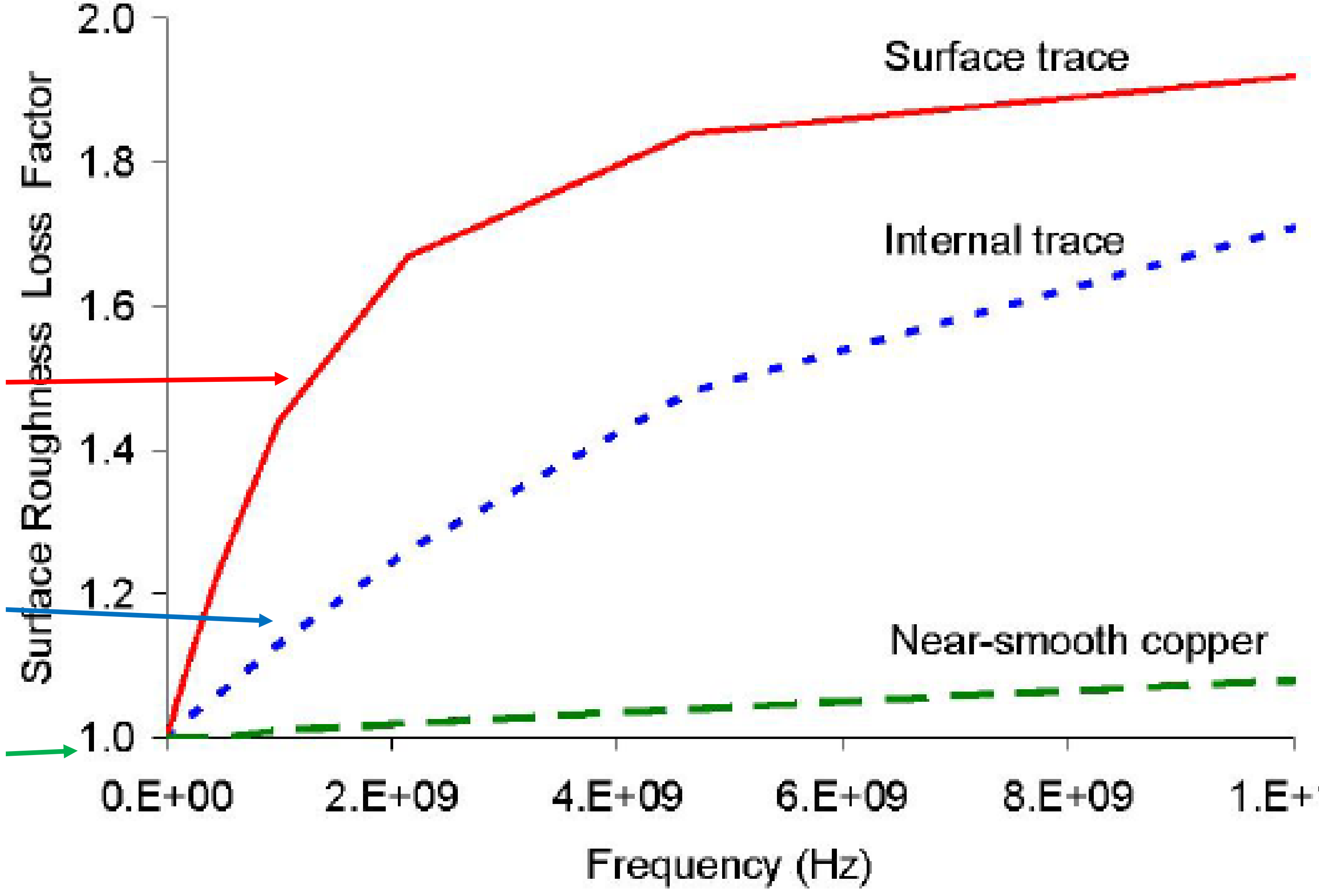


Fig. 1. Cross
internal trace (mi

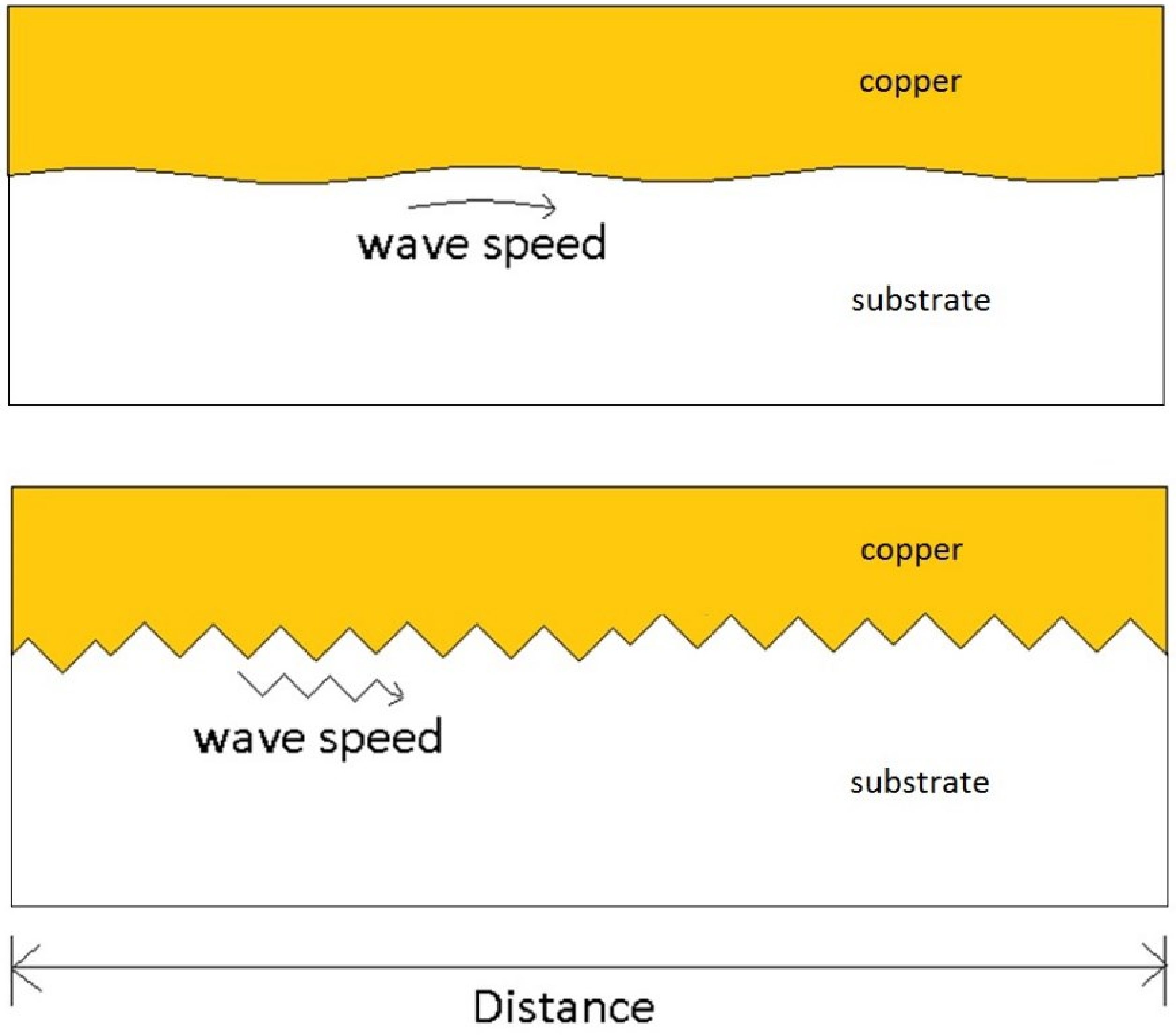


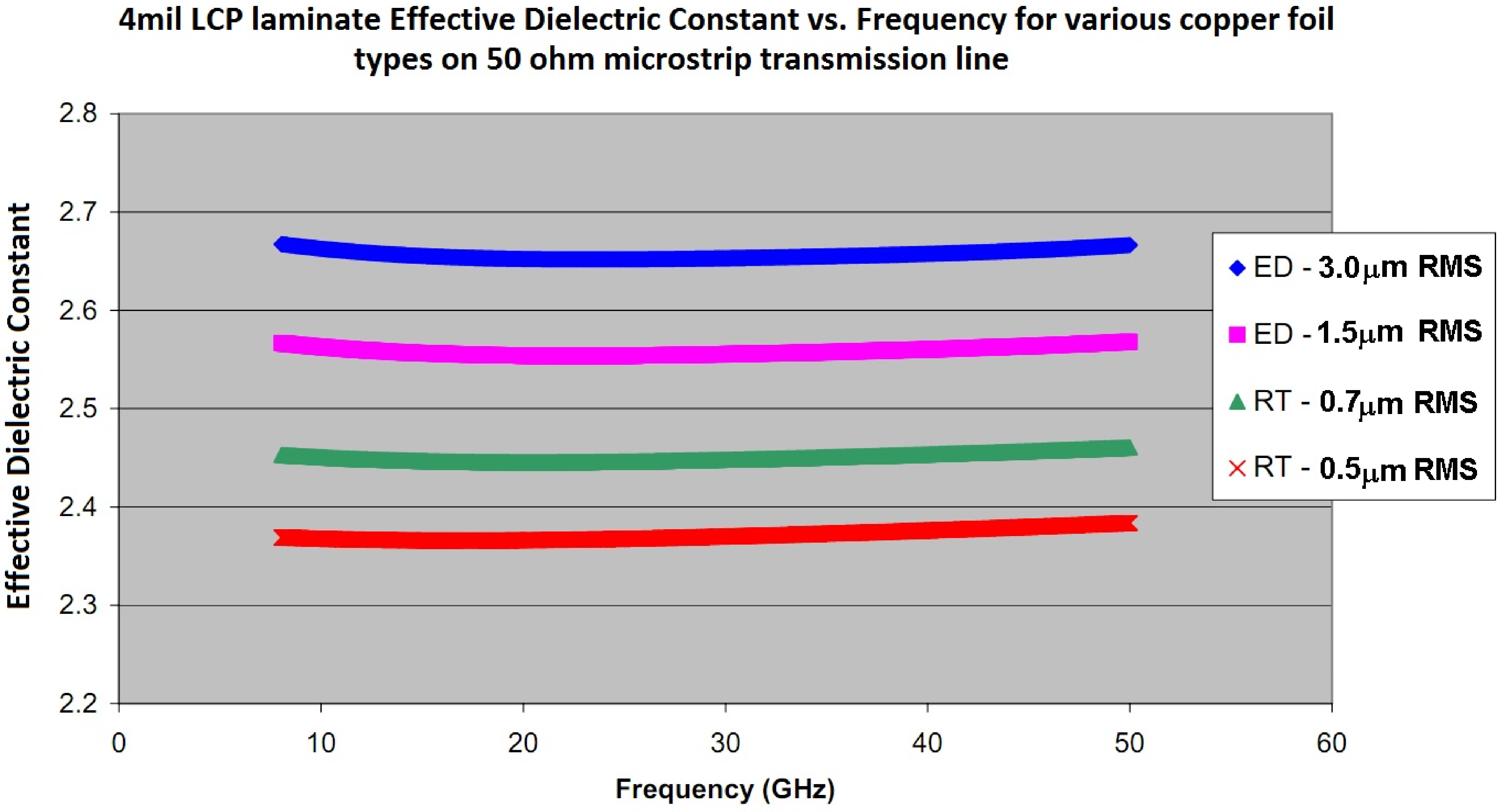


g. 2. Loss factor K_{sr} due to surface roughness effect

Tao Liang *et al.*, IEEE IMS 2006

Effect of surface roughness





But also increase the effective permittivity
=> Change the RF behavior / matching

John Coonrod, Webinar Rogers

Effect of surface roughness

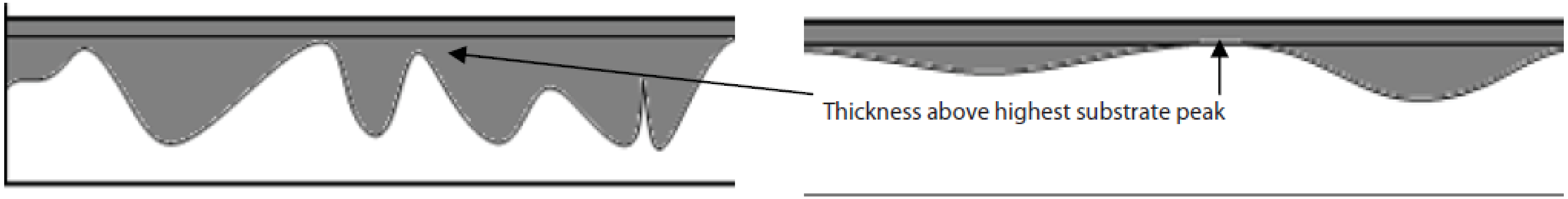


Fig. 4. Effect of surface roughness on printed conductive ink.

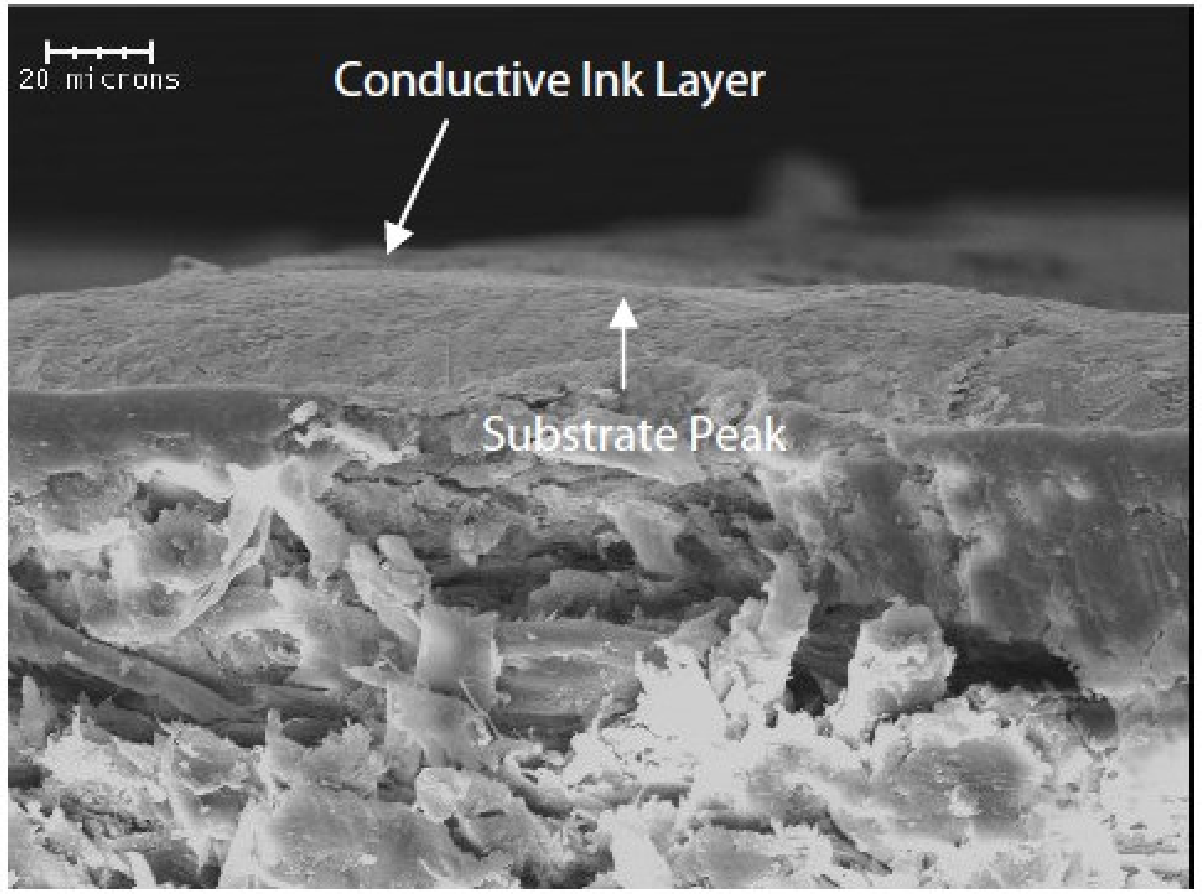


Fig. 5. SEM analysis of Substrate C, Ra = 1.61 μm.

Some cases, we need to keep certain roughness!!!

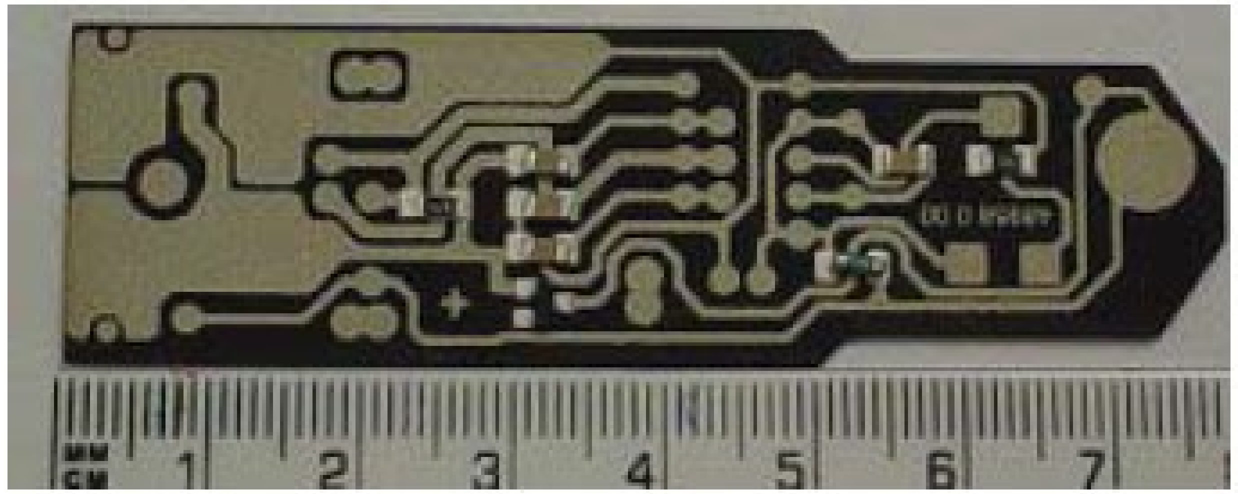


Fig. 3. Printed pattern postcuring.

Alan Ryan and Huw Lewis., IEEE T-CPMT 2012

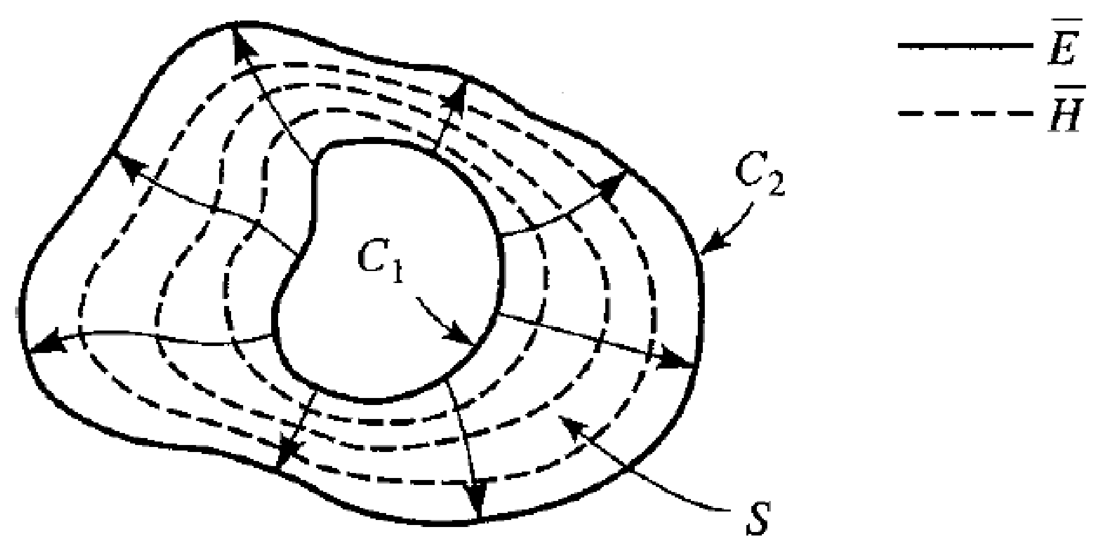
Question

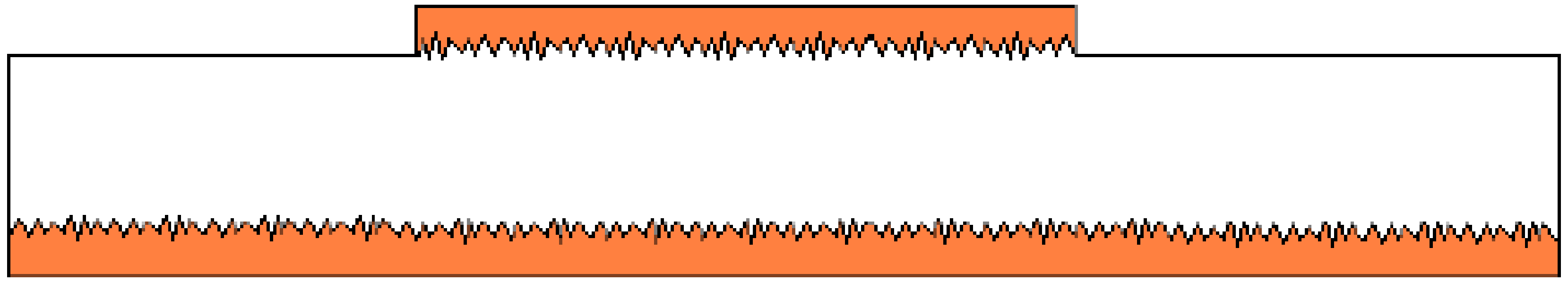
$$R = \frac{R_s}{|I_o|^2} \int_{C_1+C_2} \bar{H} \cdot \bar{H}^* dl \ \Omega/\text{m}.$$

Surface resistance: $R_s = \sqrt{\frac{\omega\mu}{2\sigma}} = \frac{1}{\sigma\delta_s}$

Skin depth: $\delta_s = \sqrt{\frac{2}{\omega\mu\sigma}}$

Field lines on an arbitrary TEM transmission line





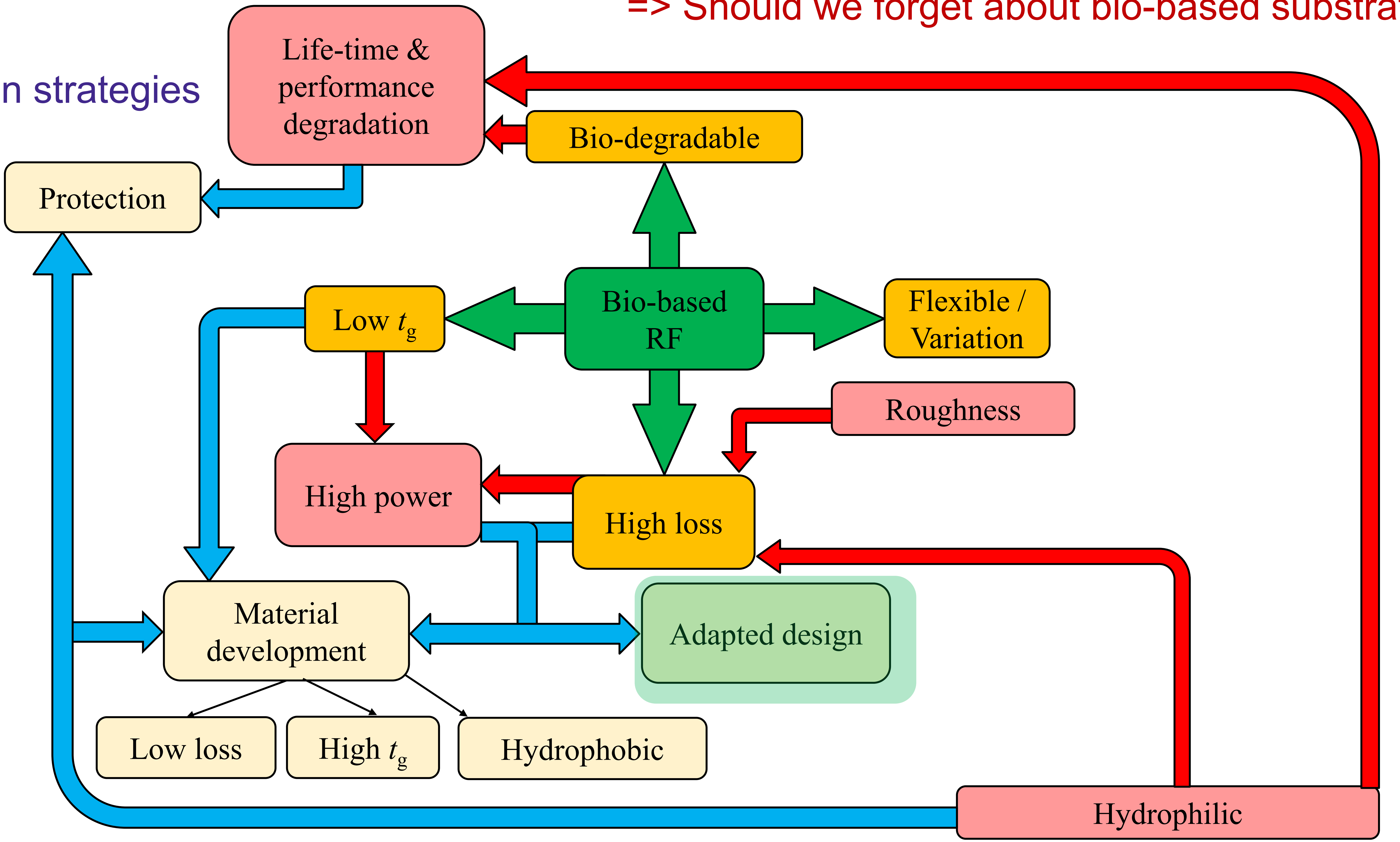
With bio-based conductor, lower conductivity σ is expected
=> Skin depth δ_s increases
=> Can we expect less losses?

John Coonrod, Webinar Rogers

Challenges with bio-based substrates

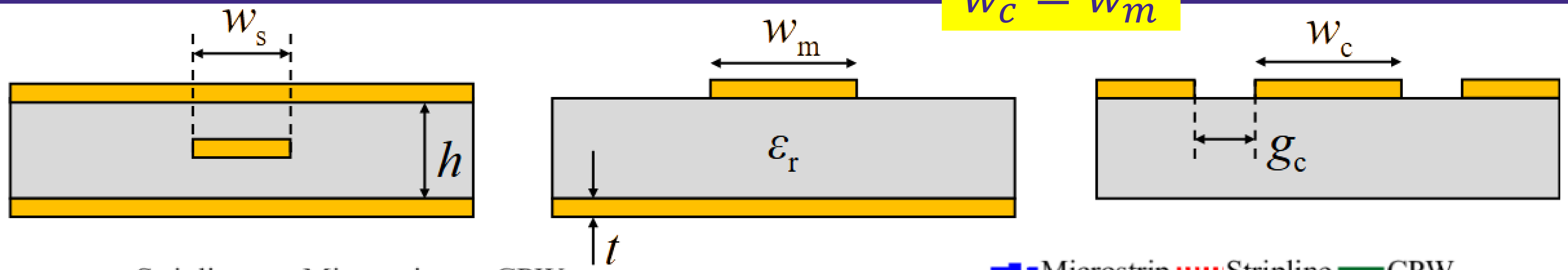
A lot of problems
=> Should we forget about bio-based substrates?

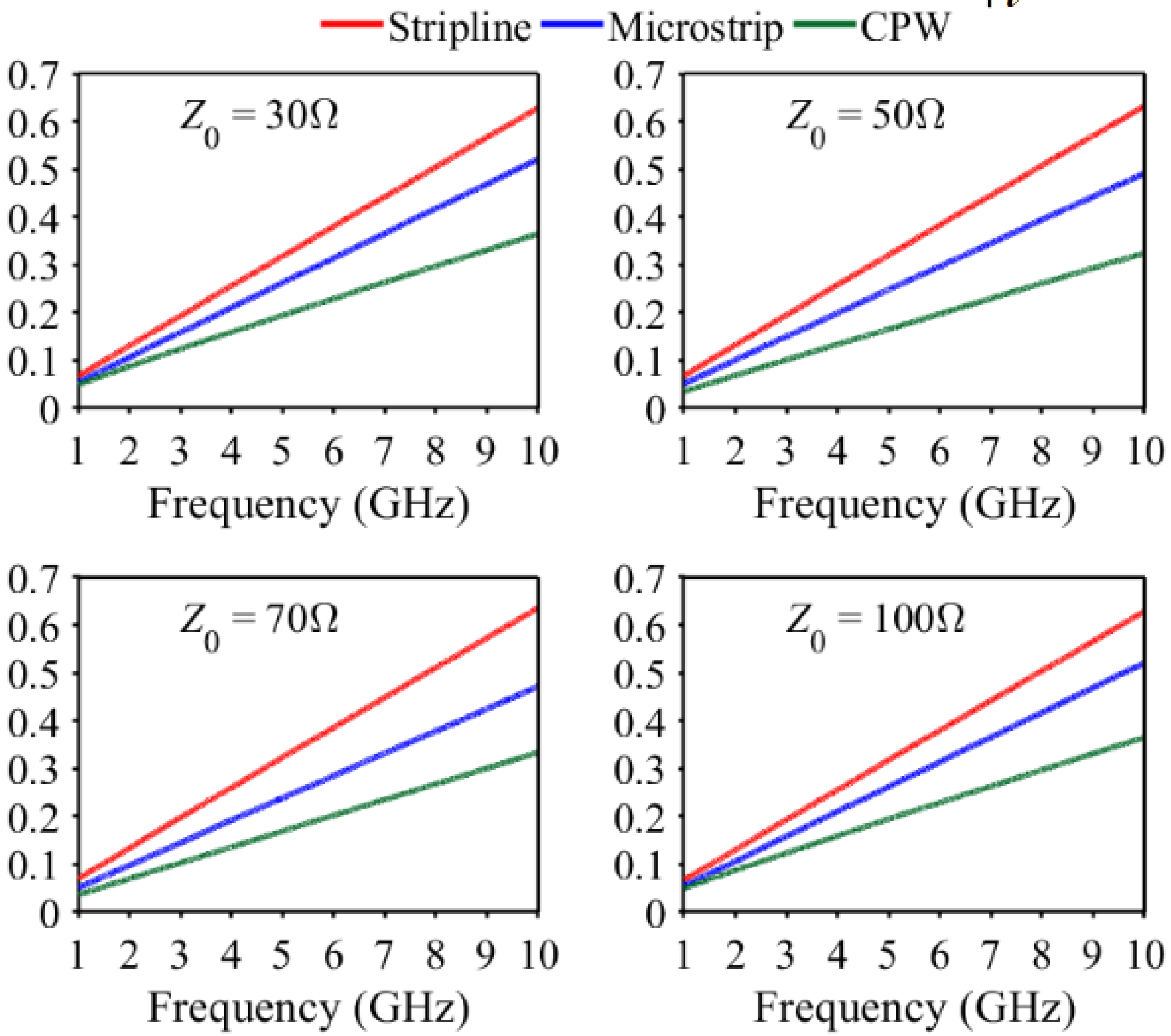
Trade off
Rethink about design strategies

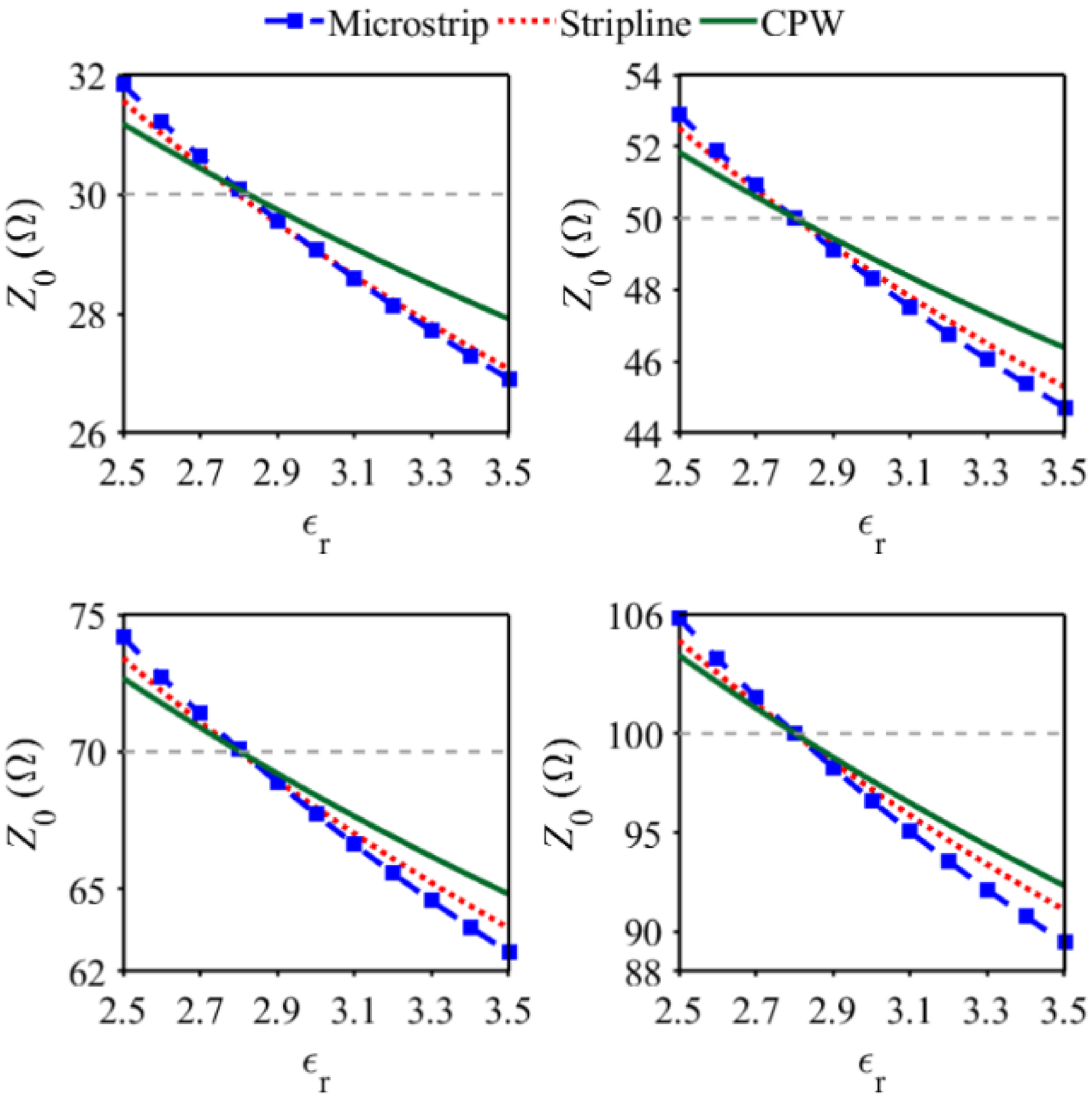


Example on transmission lines

$w_c = w_m$







CPW has the lowest loss
CPW has Z_0 variates less rapidly

R. Berro *et al.*, EuMW 2024

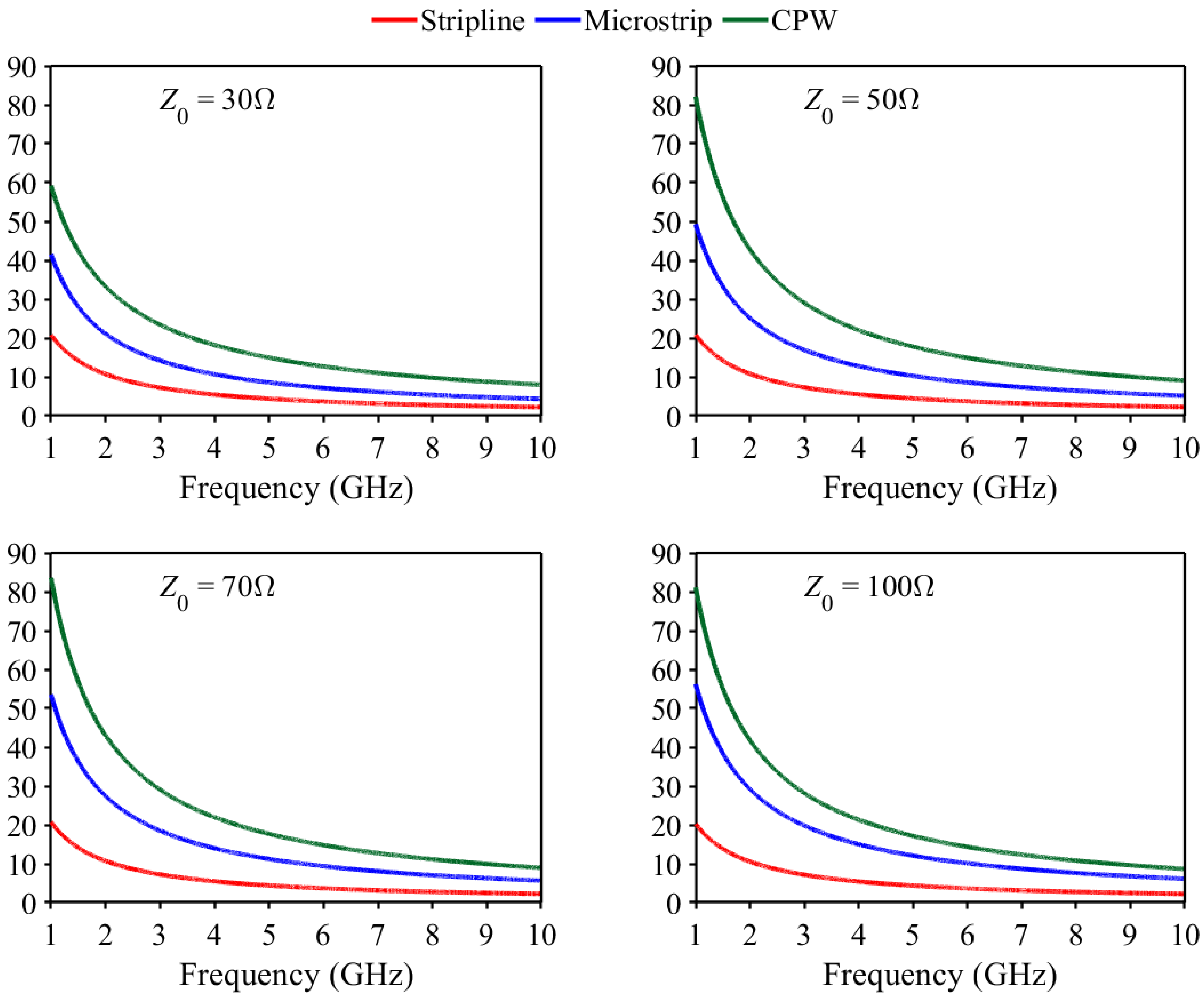
Example of a Figure-of-Merit (FoM) for transmission lines

- ➢ Same length
- ➢ Same characteristic impedance
- ➢ Same substrate & thickness
- ➢ Same conductor & thickness

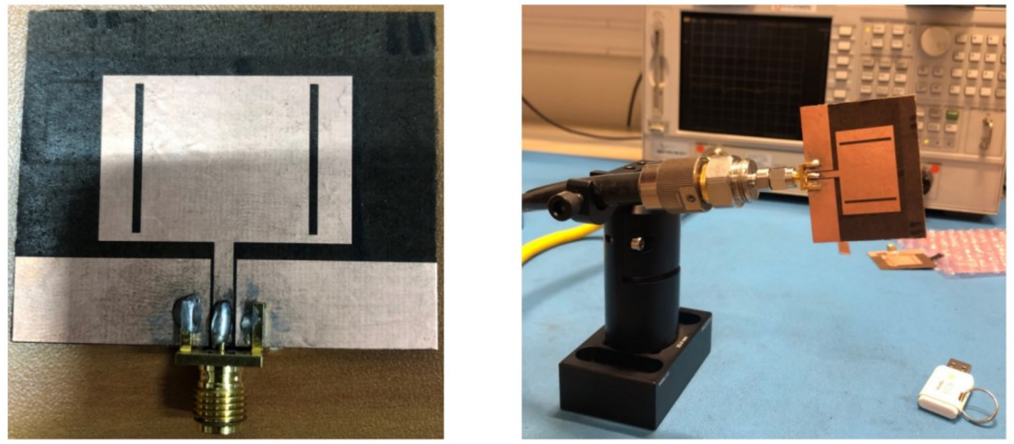
$$FoM = \frac{1}{\alpha \times W_{Cu}}$$

Condition: Impact of Dielectric << Metal

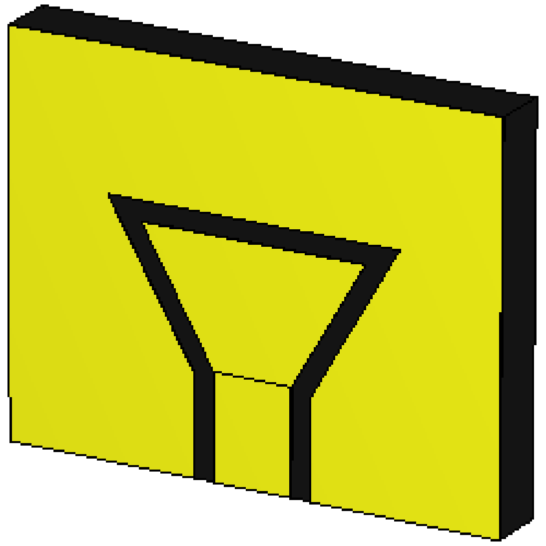
Not yet taken into account thermal dissipation, cross-talk...



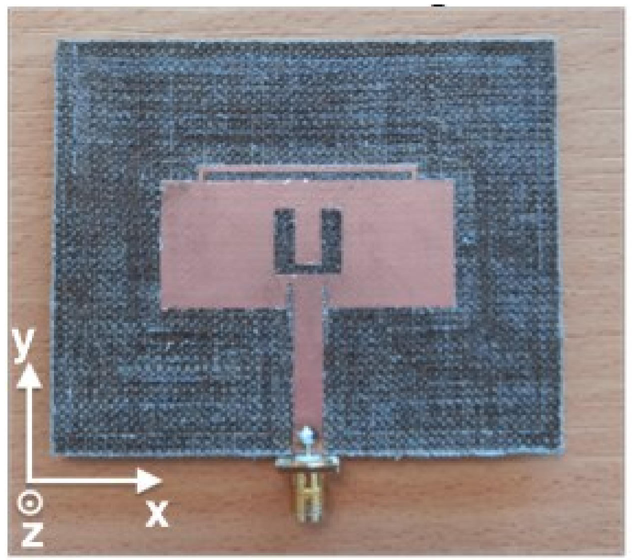
Example of some RF components using PLA/flax



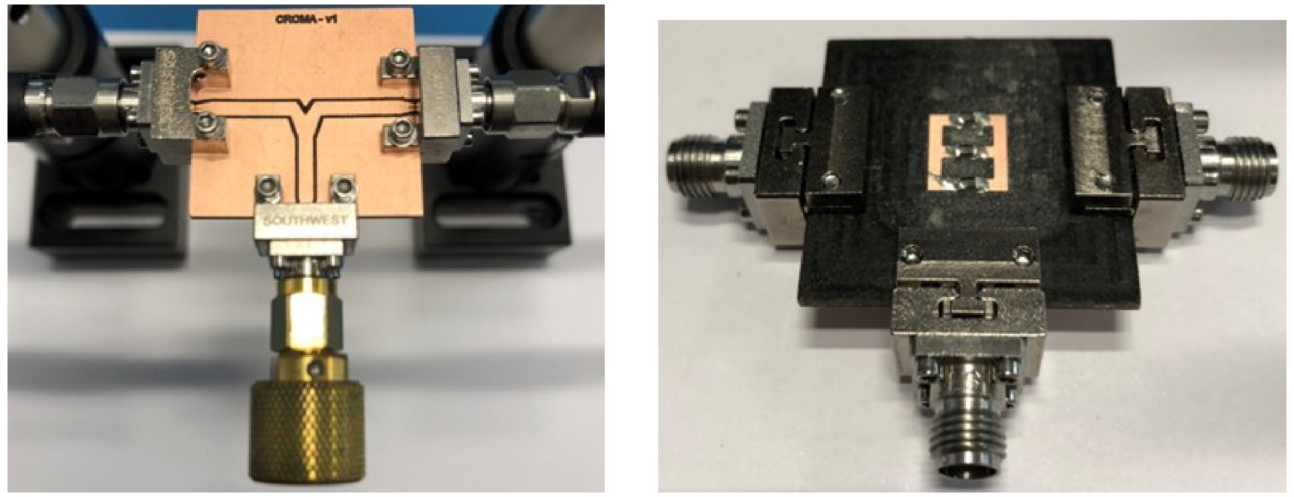
CPW fed monopole antenna
T. P. Vuong *et al.*, CROMA



CPW fed slot antenna
N. T. T. Huong *et al.*, internship FMNT at CROMA



Microstrip patch antenna
V. Grennerat *et al.*, EuCAP 2024



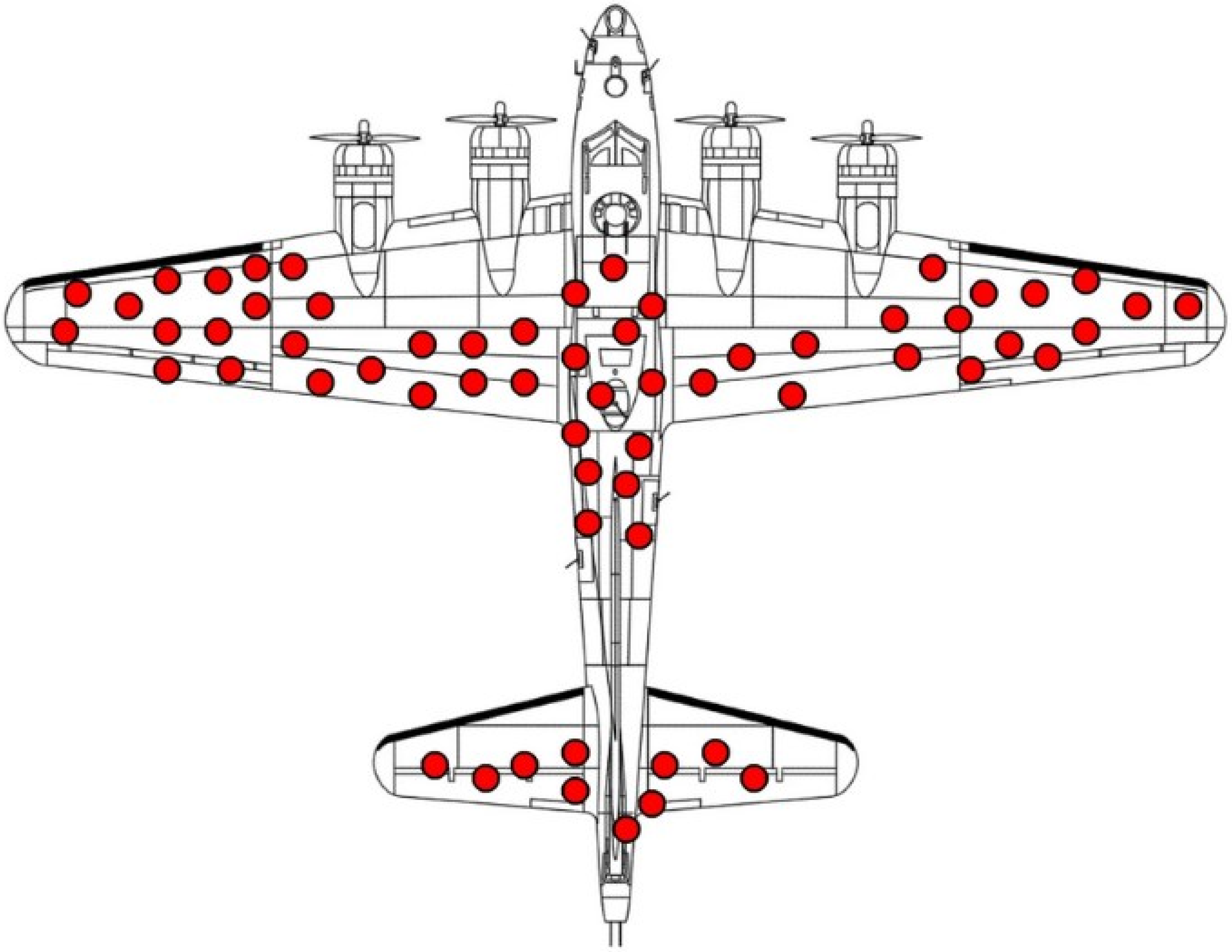
CPW power divider
R. Berro *et al.*, EuMW 2024

Figure-of-Merit

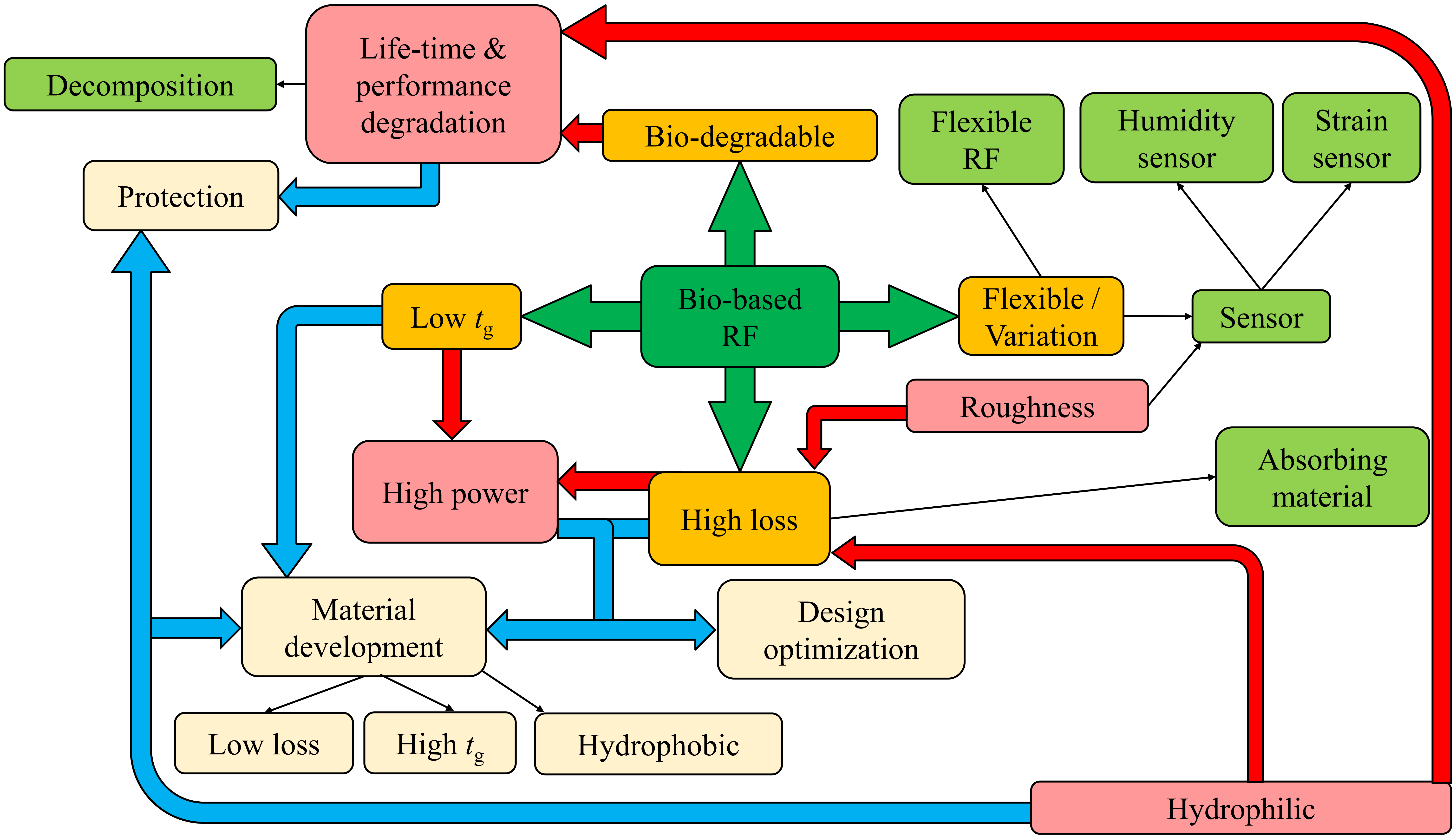
What if the condition impact of dielectric << metal no longer valid?

$$FoM = \frac{\Delta(CO2eq\ - fab)}{\frac{\Delta(CO2eq\ - use)}{1days} \times active\ days}$$

“Reverse” thinking



Make the weakness become strength



Example: Absorbing materials

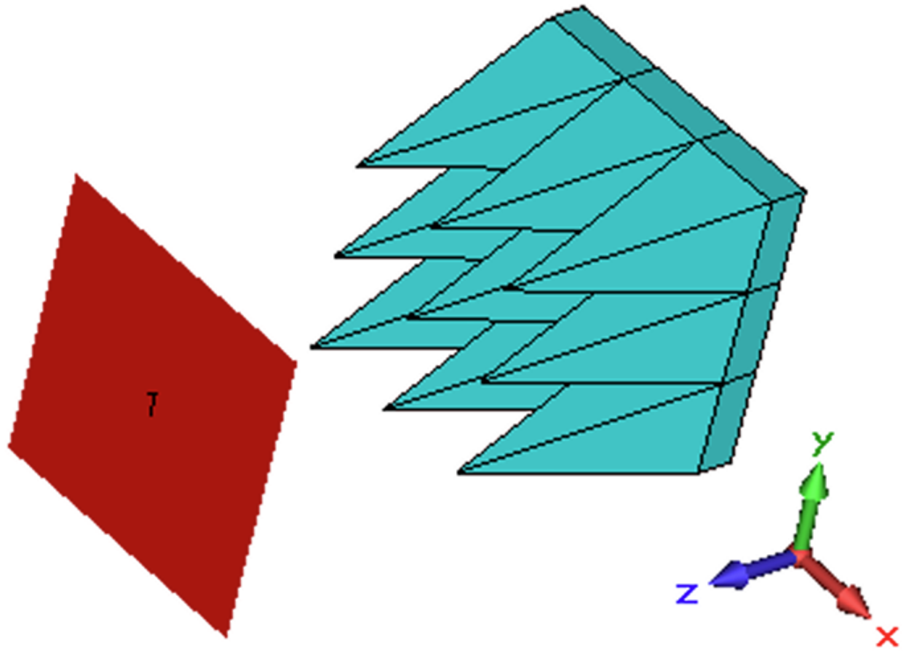


Fig. 5. 9 tips of pyramidal microwave absorber in CST Microwave Studio.

Fig. 6. Fabricated banana leaves-polyester-MEKP pyramidal microwave absorber in pyramidal mould

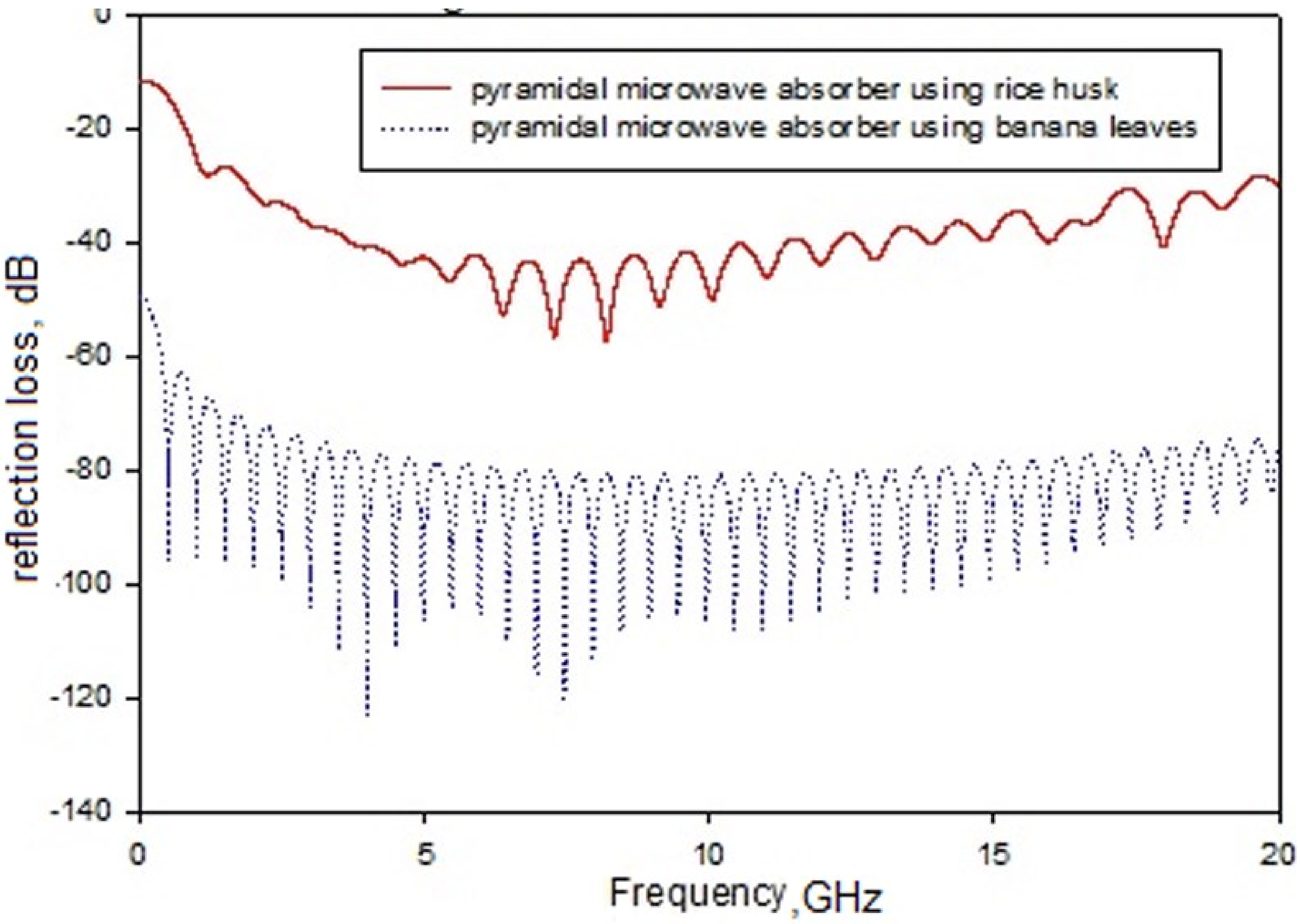
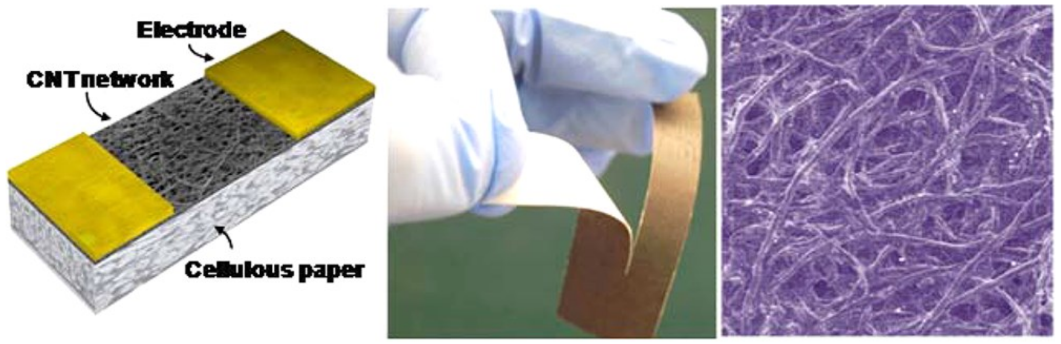


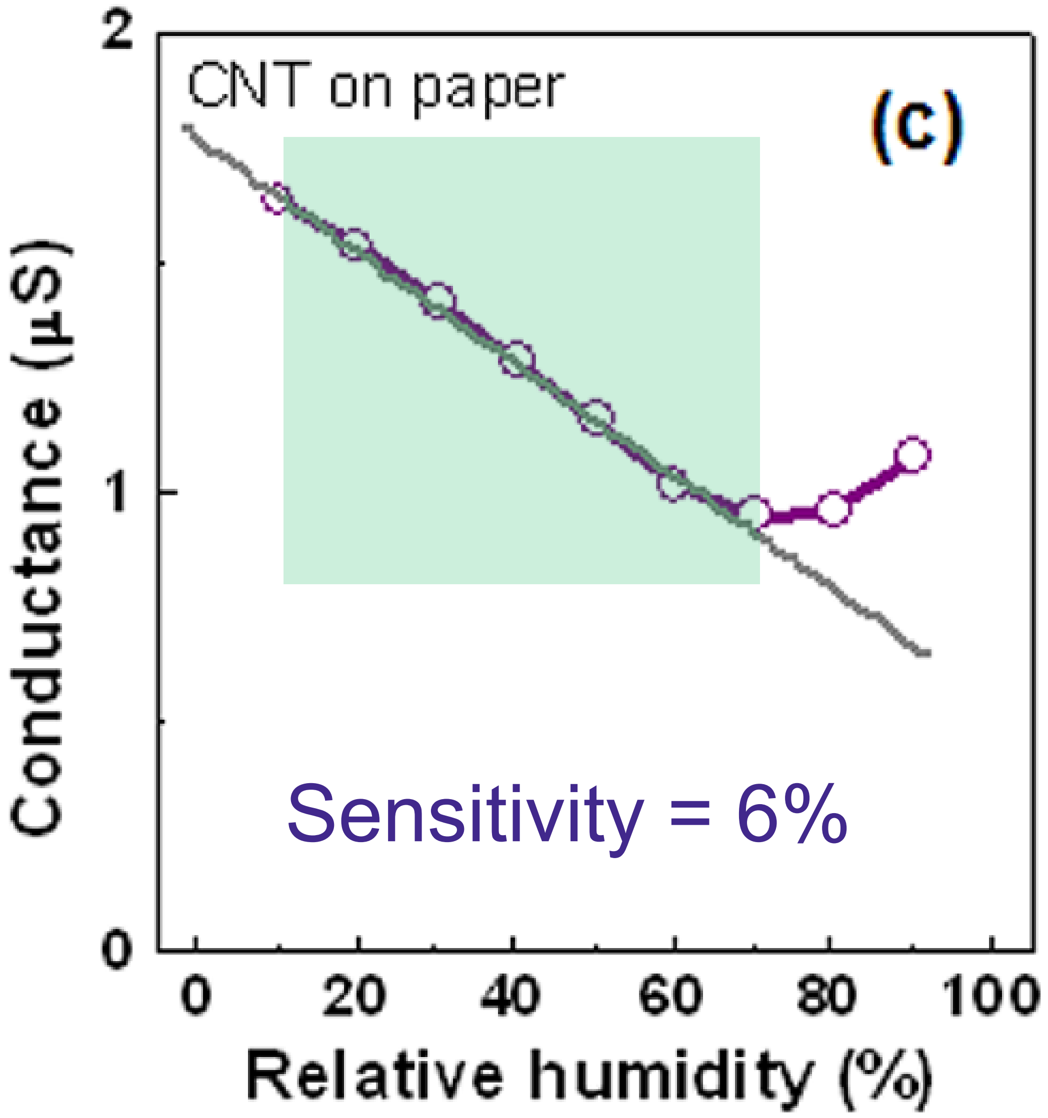
Fig. 11. Reflection loss of pyramidal microwave absorber

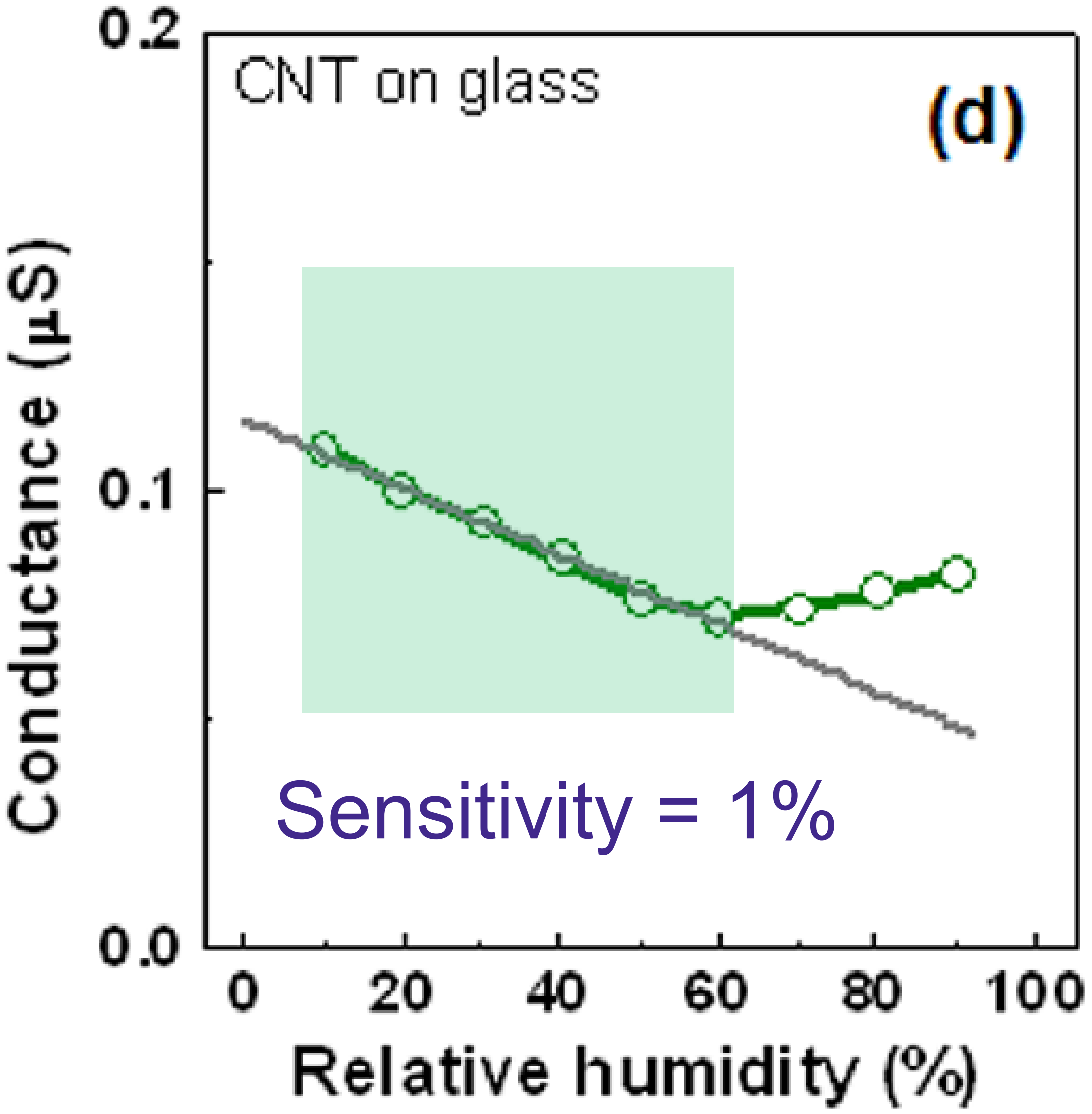
Z. S. Farhany *et al.*, IEEE ISWTA 2012

Example: Resistive Humidity Sensor



"the roughness and porosity are attractive here because they increase the contact area with the ambient air and promote the adhesion to CNTs."





$$Sensitivity = \frac{S_x - S_0}{S_0} \times \frac{1}{RH_x - RH_0}$$

J-W. Han *et al.*, Journal of Physical Chemistry C, 2012

Example: Bio-degradable

Summary

- Life Cycle Assessment (LCA) can be used to help decision maker but only valid for a very specific scenario and do not take into account cost / social impact.
- Alternative / complement could be considered: Life Cycle Cost, Environmental Impact Assessment
- A Figure of merit could be introduced in design phase to find the best compromise between environment / performance
- “Reverse” thinking
- Some potentials approaches: modular, reconfigurable, refuse…

Thank you!

BIG QUESTIONS

Bringing life to debate

nhu-huan.nguyen@grenoble-inp.fr