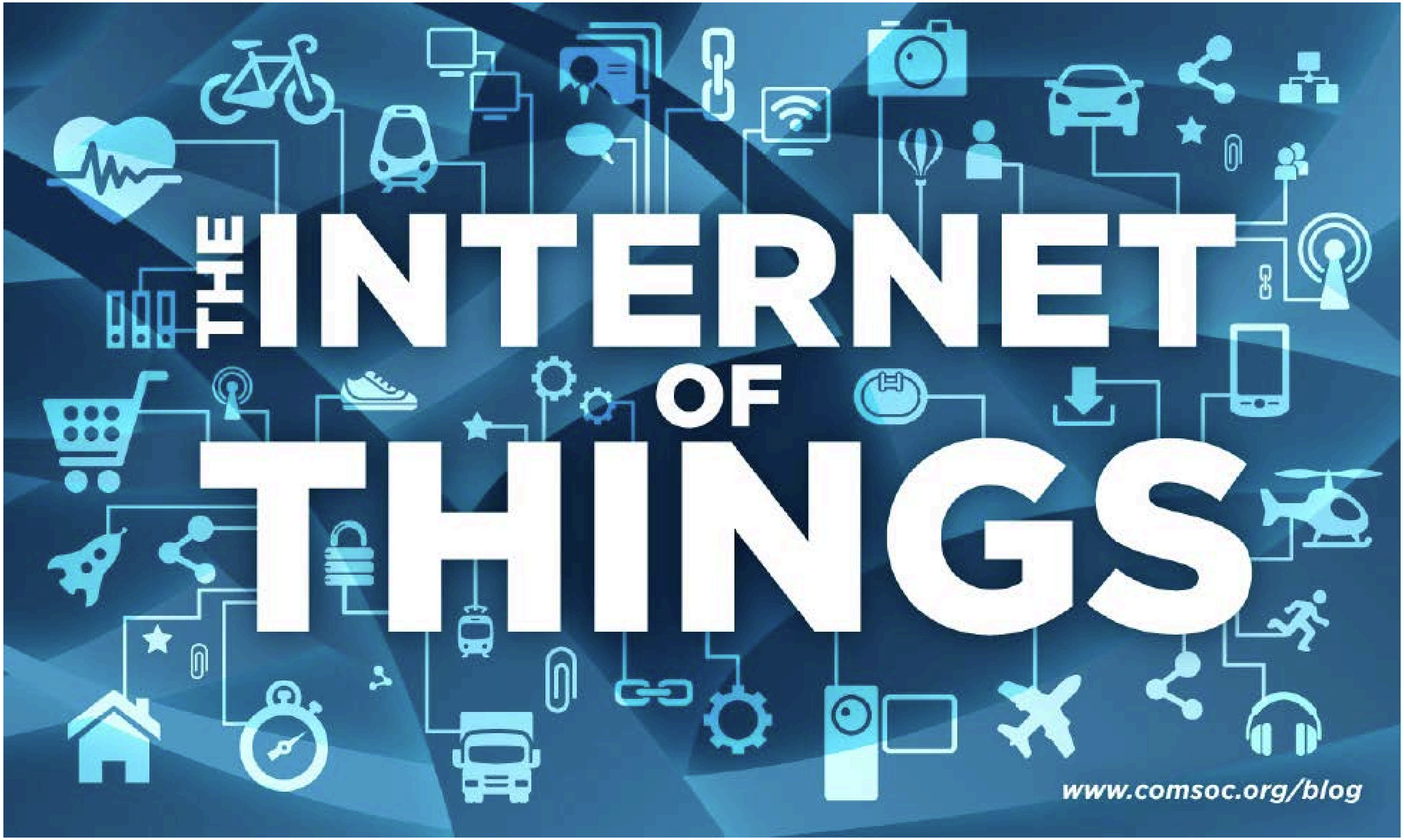
Micro- and millimeter-wave electronic circuits on cellulose substrates: promising means for the development of the IoT physical layer

UNIVERSITÀ DEGLI STUDI DI PERUGIA

Luca Roselli

The vision…



The reality…

Electronics: from problem to solution

Networked Society – IoT and WAE

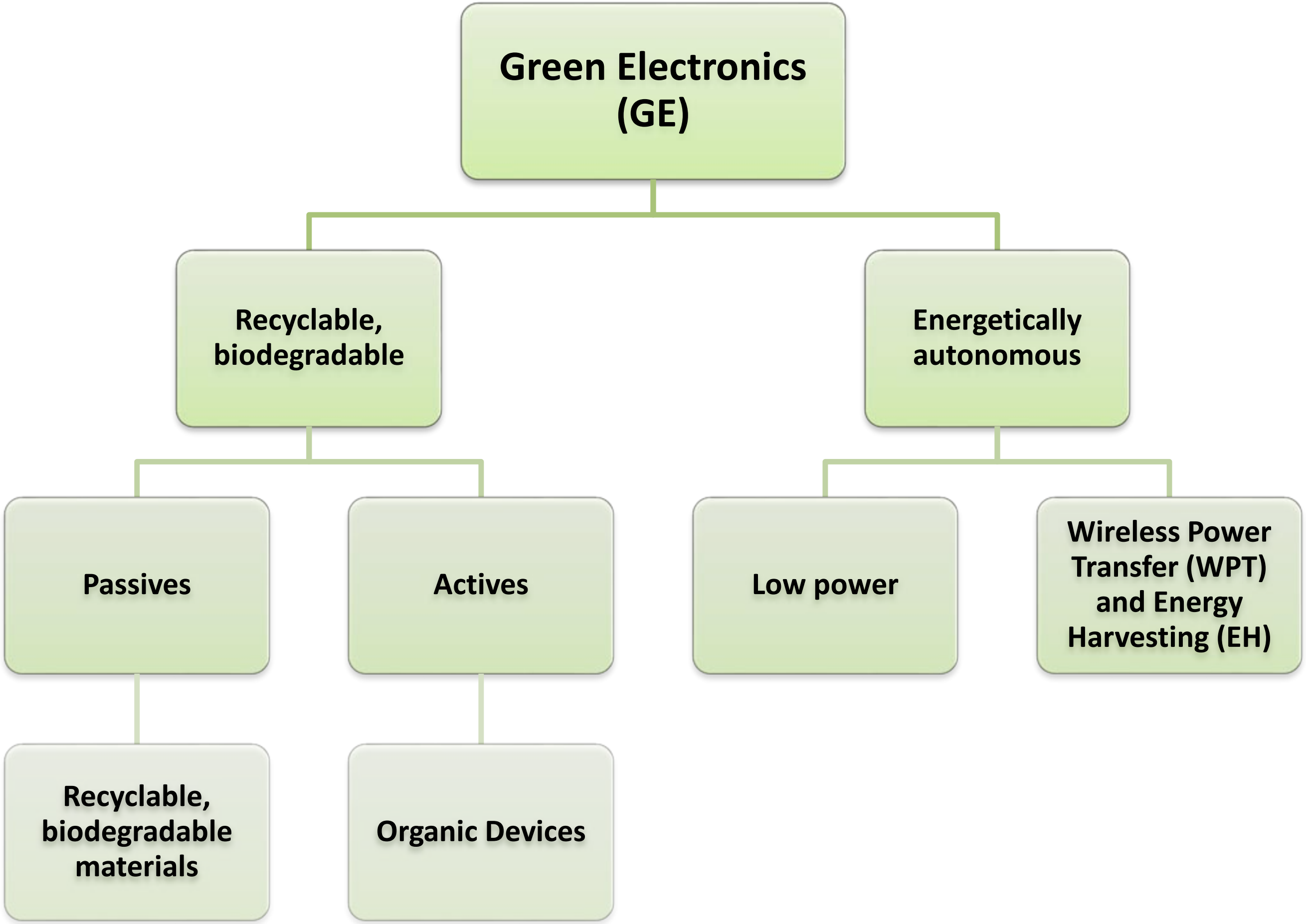
More and more electronics spread all over the planet

Pollution of electronic circuits

Power supply impossible

Environmentally friendly and autonomous electronics

Solutions


Green Electronics (GE)
Recyclable, biodegradable
Energetically autonomous
Passives
Actives
Low power
Wireless Power Transfer (WPT) and Energy Harvesting (EH)
Recyclable, biodegradable materials
Organic Devices

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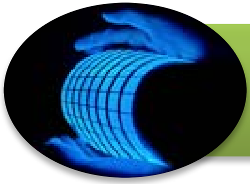
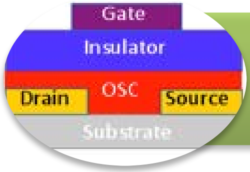
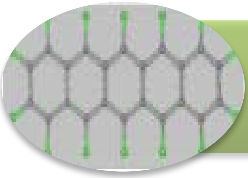
Technologies and materials



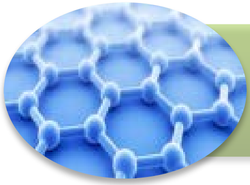
OLED



OTFT



OSM



Graphene

Paper

Bioplastic

PET

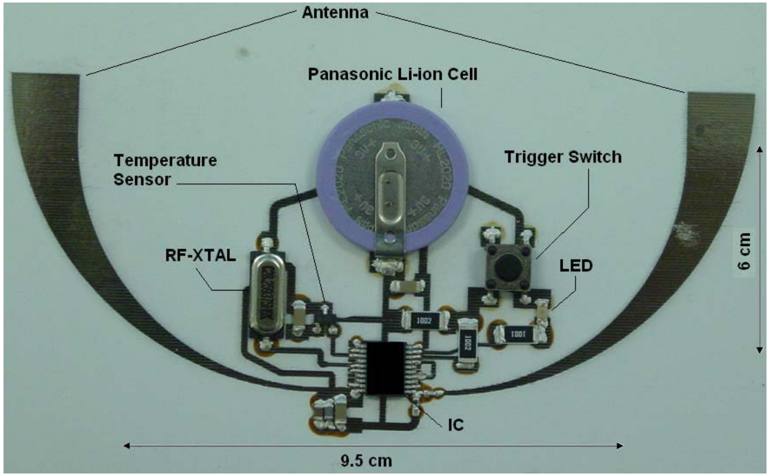
... ...

... ...

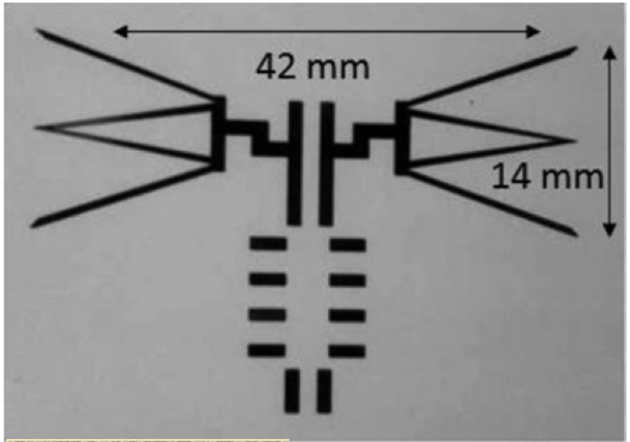
HF lab

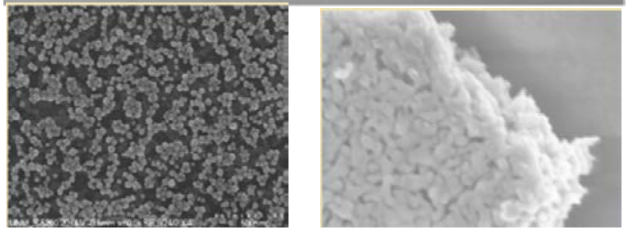
RF circuits on cellulose: UNIPG-HFE developments "Some bricks in the wall"

Ink-jet printed RF electronics



After Tentzeris et al. “Novel enhanced-thickness…”, IEEE-IMS, 2008.





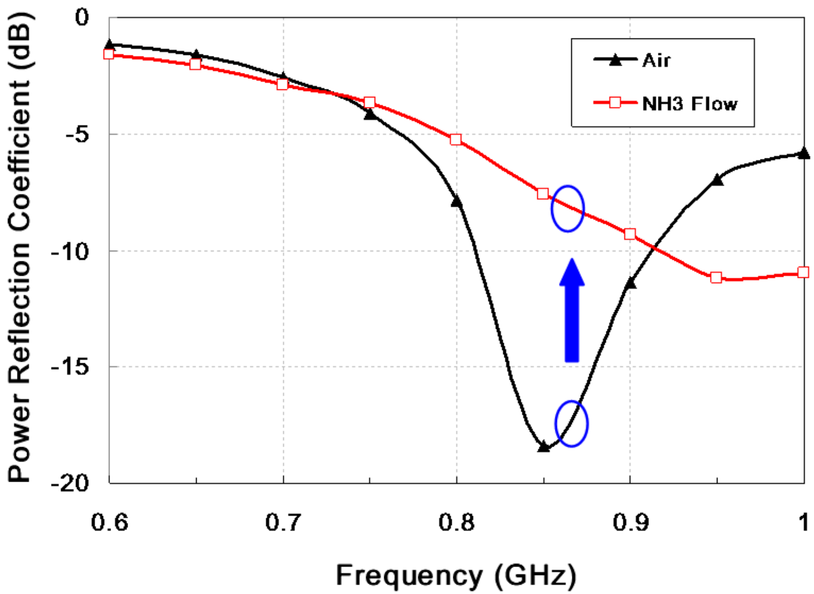
Ag ink before sintering

Ag ink after sintering

•Ag ink needs sintering at 150° for 15m
•Cured Ag ink conductivity = 1/5 of solid copper

G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M. M. Tentzeris, and L. Roselli, “Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology,” IET Microwaves, Antennas Propag., vol. 5, no. 8, p. 993, 2011. IET-MAP BEST PAPER AWARD 2013.

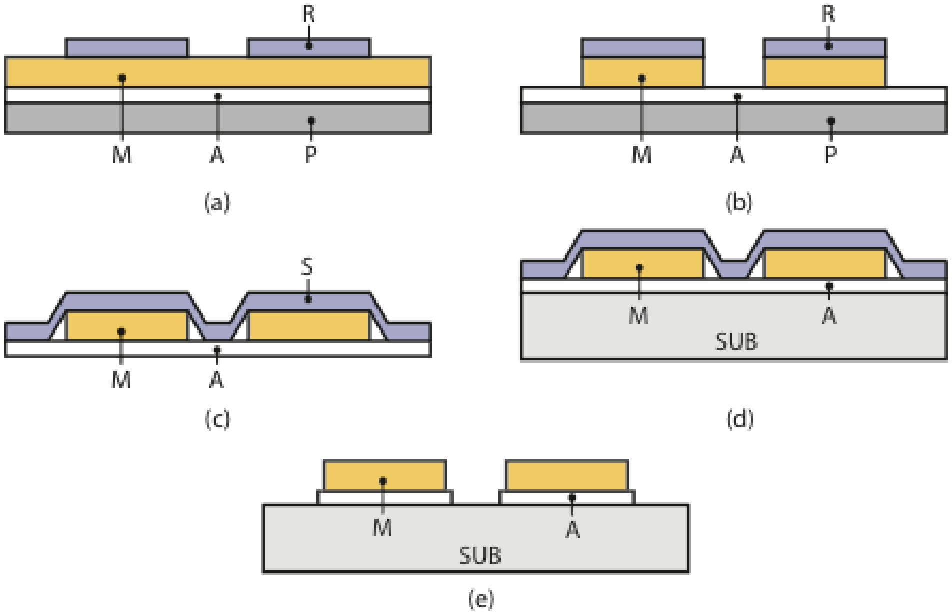
SWCNT inkjet printed chip-less gas sensor



- Antenna on cellulose loaded with CNT layer
- The CNT layer acts as a resistor sensitive to NH3 concentration
- Impedance changes are yeld variations of the backscattered power level

R. Vyas, V. Lakafosis, H. Lee, G. Shaker, L. Yang, G. Orecchini, A. Traille, M. M. Tentzeris, and L. Roselli, "Inkjet Printed, Self Powered, Wireless Sensors for Environmental, Gas, and Authentication-Based Sensing," IEEE Sensor J. vol. 11, no. 12, pp. 3139–3152, Dec. 2011.

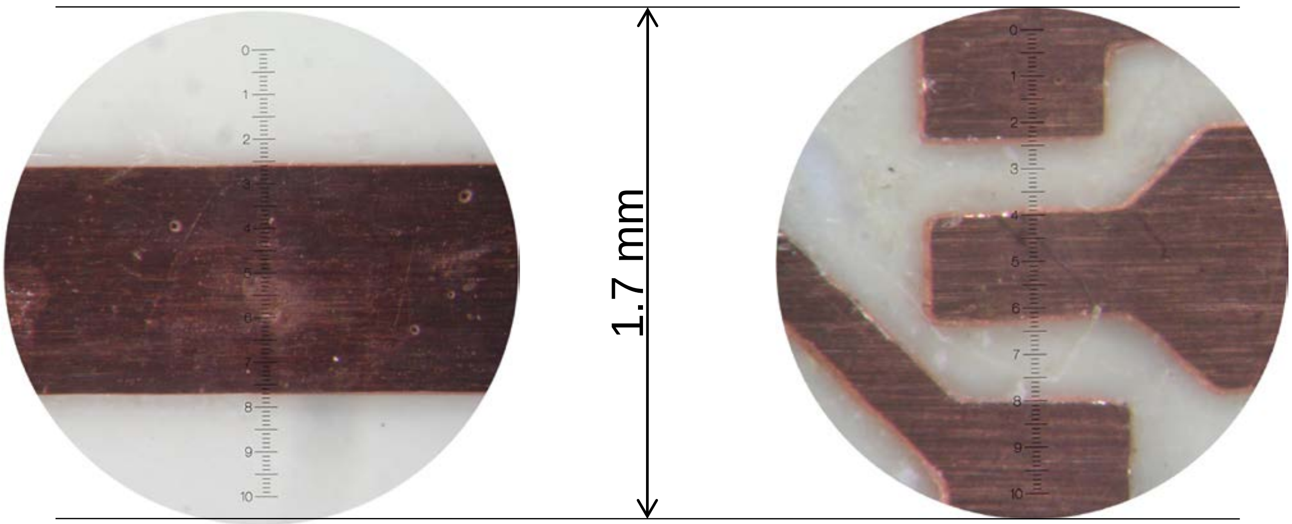
Adhesive copper laminate (1/2)



- The adhesive copper tape is etched by photo-lithography
- The layout is transferred to the hosting substrate via sacrificial layer

F. Alimenti, P. Mezzanotte, M. Dionigi, M. Virili, and L. Roselli, “Microwave Circuits in Paper Substrates Exploiting Conductive Adhesive Tapes,” IEEE Microw. Wirel. Comp. Lett., vol. 22, no. 12, pp. 660–662, 2012.

Adhesive copper laminate (2/2)



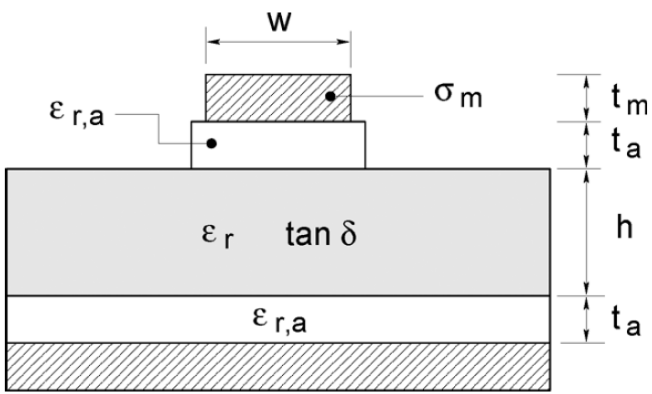
Technology features:

- 35 μm thick solid copper (σ = 5.8x10^8 S/m)
- Mechanical resolution 150μm pitch
- No sintering required
- Compatibility with conventional soldering technology

Microstrip line on paper (1/2)

PARAMETERS OF THE MICROSTRIP LINE

Parameter	Value		Parameter	Value	
w	900	μm	ε_r	3.2	
h	250	μm	$\tan\delta$	0.08	
t_a	30	μm	$\varepsilon_{r,a}$	1.3	
t_m	35	μm	σ_m	5.8×10^7	S/m



Parameter	Value	
ε_r(eq)	2.55	
$\tan\delta$(eq)	0.05	
h(eq)	370	μm

Mariotti, C.; Alimenti, F.; Mezzanotte, P.; Dionigi, M.; Virili, M.; Giacomucci, S.; Roselli, L., "Modeling and characterization of copper tape microstrips on paper substrate and application to 24 GHz branch-line couplers," European Microwave Conference (EuMC), 2013 , vol. 1, pp.794,797, 6-10 Oct. 2013

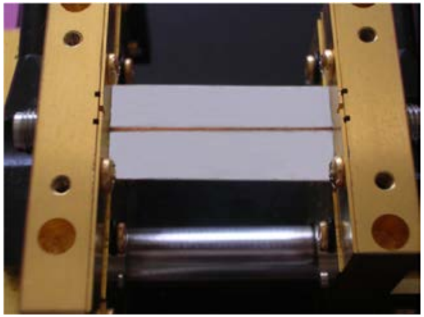
Microstrip line on paper (2/2)

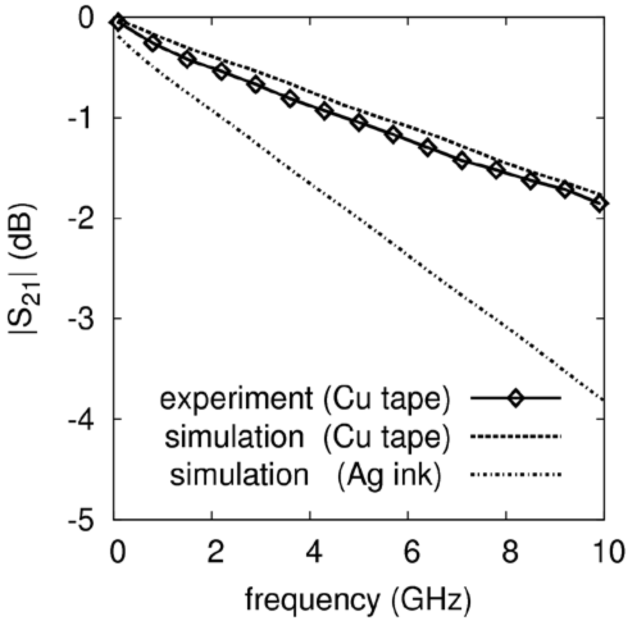
Insertion loss @ 10 GHz

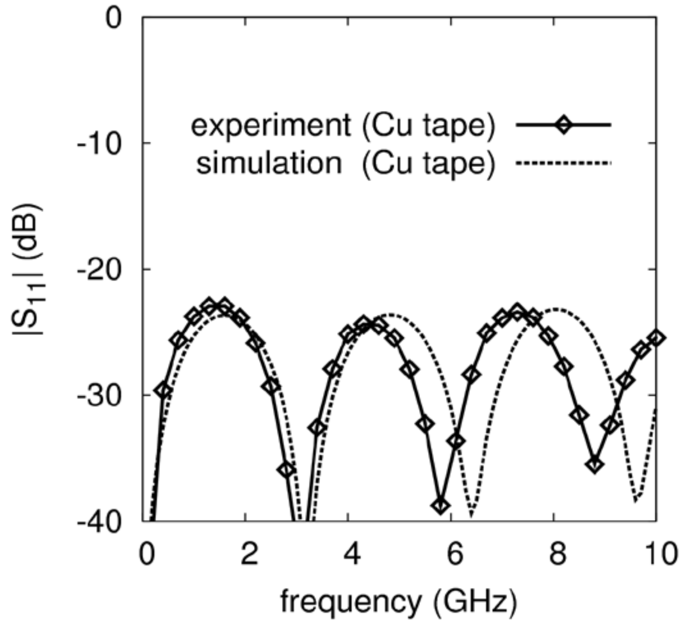
•Mitsubishi photo paper

•Cu tape: 0.6 dB/cm

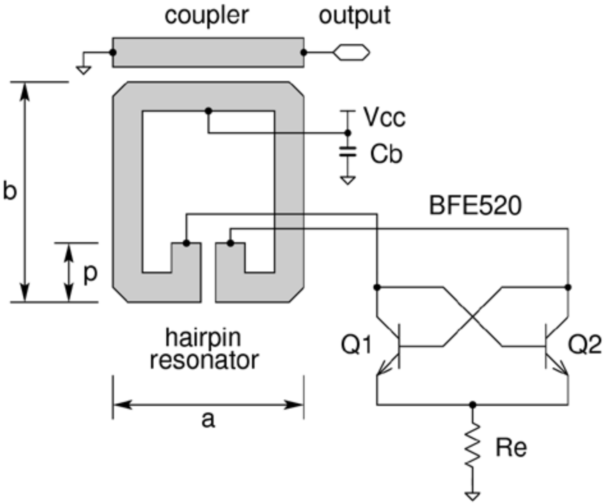
•Ag ink: 1.3 dB/cm

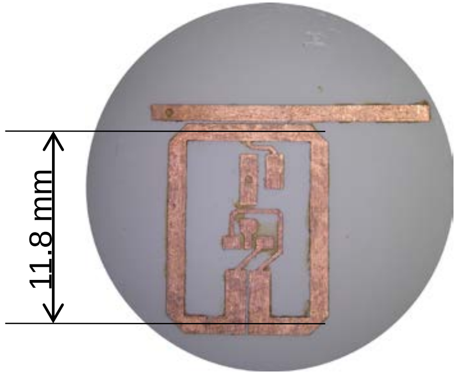


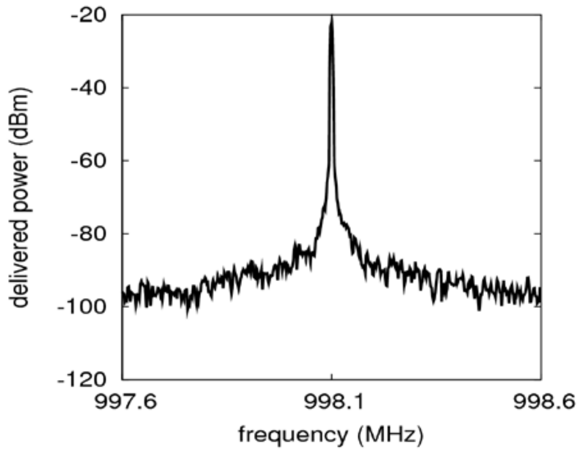




Low-power UHF oscillator (1/2)







Features

•**Hairpin resonator** in microstrip technology.

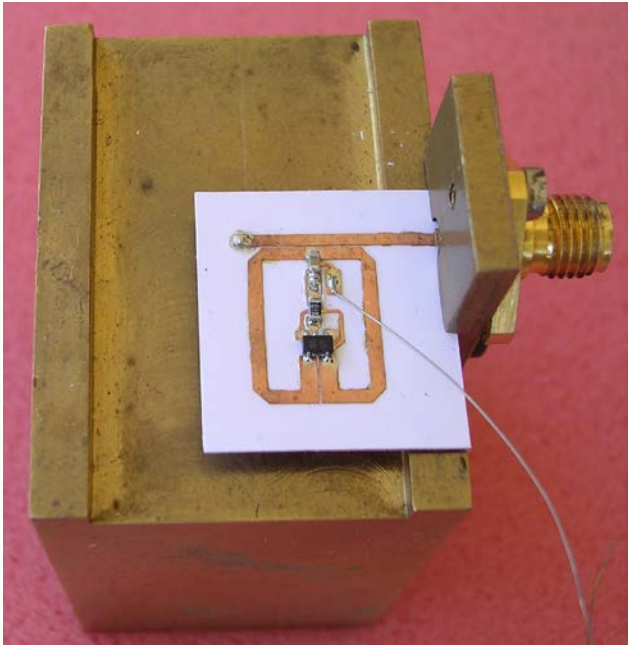
•f0=998 MHz.

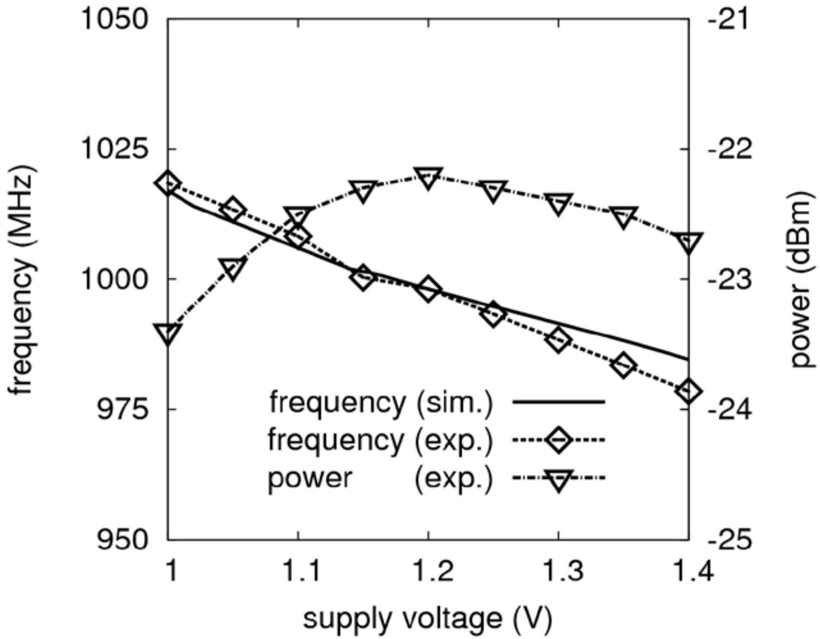
•-20 dBm output power.

•**0.9 mW @ 1.2 V supply**

F. Alimenti, C. Mariotti, P. Mezzanotte, M. Dionigi, M. Virili, and L. Roselli, "A 1.2 V, 0.9 mW UHF VCO Based on Hairpin Resonator in Paper Substrate and Cu Adhesive Tape," IEEE Microw. Wirel. Components Lett., vol. 23, no. 4, pp. 214–216, Apr. 2013.

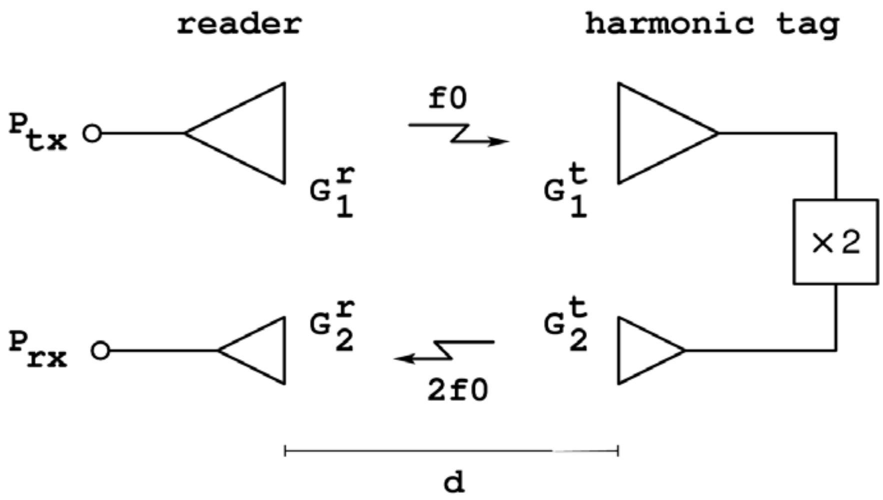
Low-power UHF oscillator (2/2)





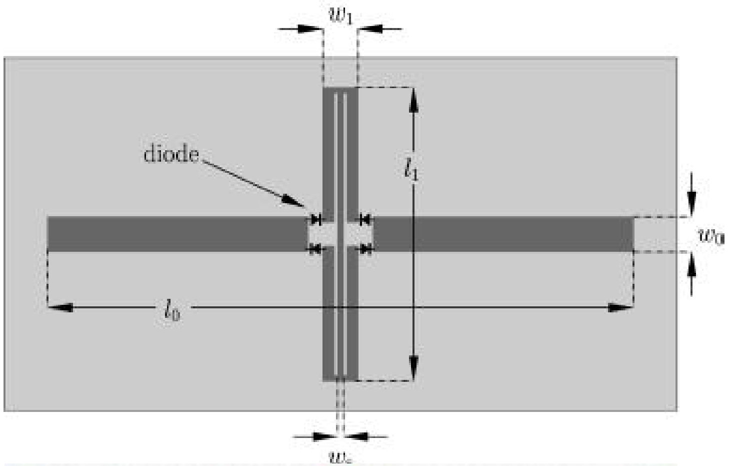
- Only 3 SMT components (BJT, resistor, bypass capacitor).
- Tuning achieved by supply voltage variation.

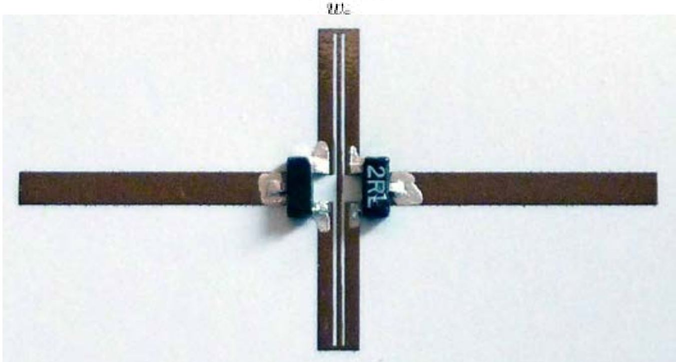
Harmonic RFID Systems

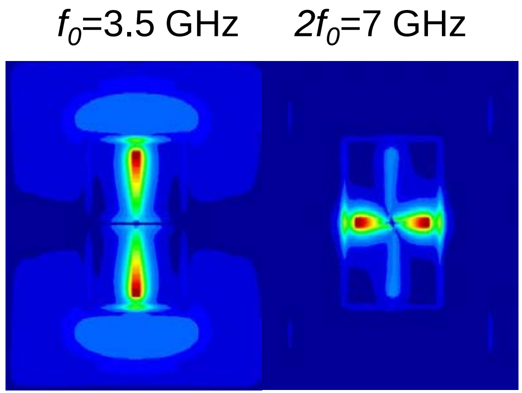


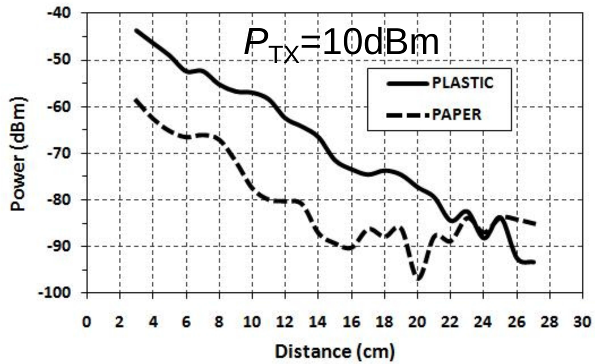
- The **reader interrogates** the environment **at f0** (fundamental).
- The tag contains a frequency multiplier (typically a frequency doubler) and **answers at n×f0** (for a doubler at 2×f0).
- **1-bit RFID system (it can determine the presence of the tag)**
- **it is insensitive to the environment backscattering**

Crossed-dipole tag









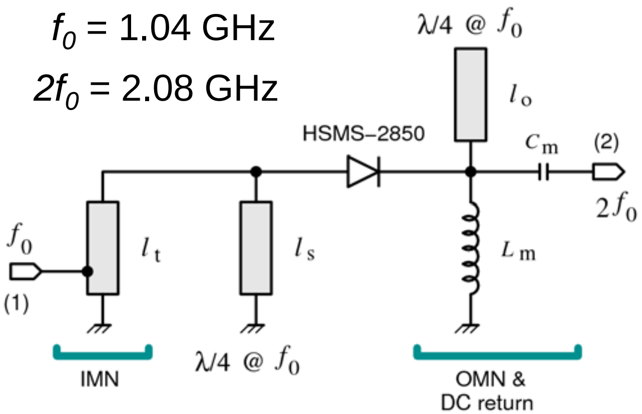
[1] S. Helbing, M. Cryan, F. Alimenti, P. Mezzanotte, L. Roselli, and R. Sorrentino, “Design and Verification of a Novel Crossed Dipole Structure for Quasi-Optical Frequency Doublers,” IEEE MGWL., vol. 10, pp. 105–107, 2000.

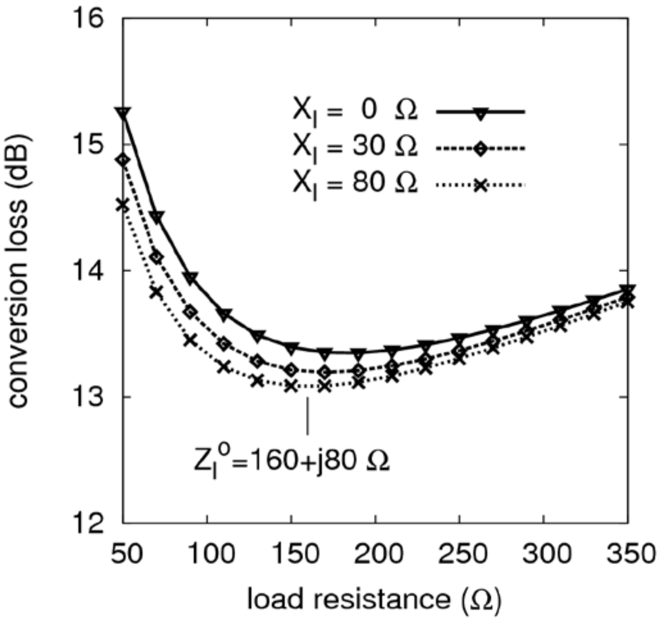
[2] G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M. M. Tentzeris, and L. Roselli, “Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology,” IET Microwaves, Antennas Propag., vol. 5, no. 8, p. 993, 2011. IET-MAP BEST PAPER AWARD 2013.

Microstrip frequency doubler (1/2)

f_0 = 1.04 GHz

$2f_0$ = 2.08 GHz

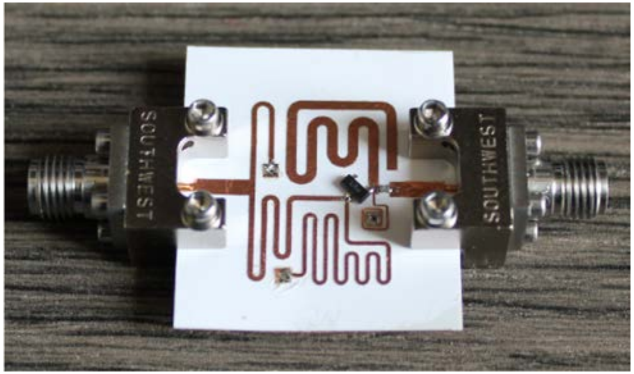




- Low-barrier Schottky diode (HSMS 2850).
- Input & output harmonic terminations implemented with λ/4 stubs.
- IMN: tapped impedance transformer.
- OMN: optimized by load-pull simulations.
- **Minimum component count → suitable for harmonic RFID tags on cellulose**

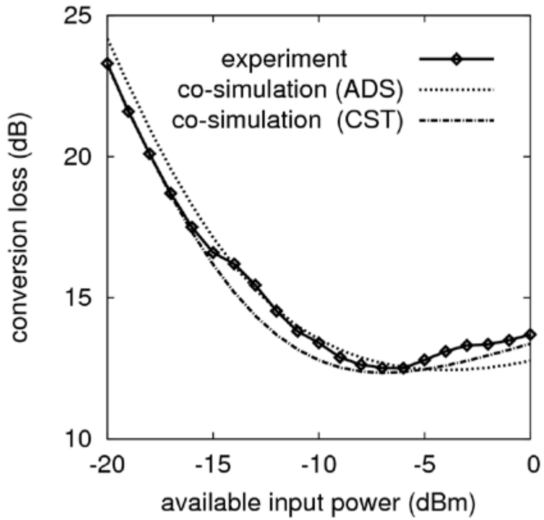
V. Palazzi, F. Alimenti, P. Mezzanotte, M. Virili, C. Mariotti, G. Orecchini, L. Roselli, “Low-Power Frequency doubler in cellulose-based materials for harmonic RFID applications,” Accepted for publication on IEEE Microwave Wireless Components Letters, 2014.

Microstrip frequency doubler (2/2)

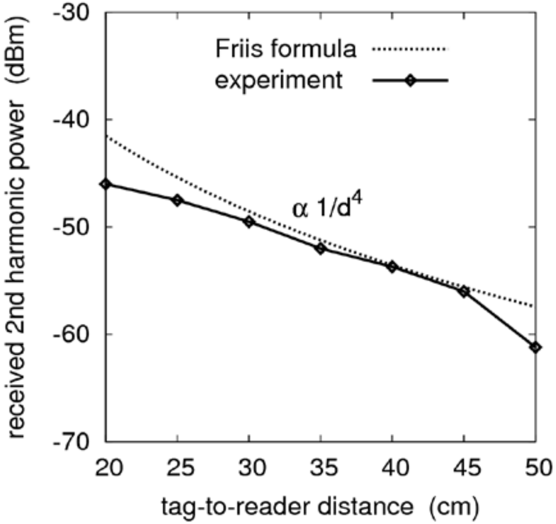


Features:

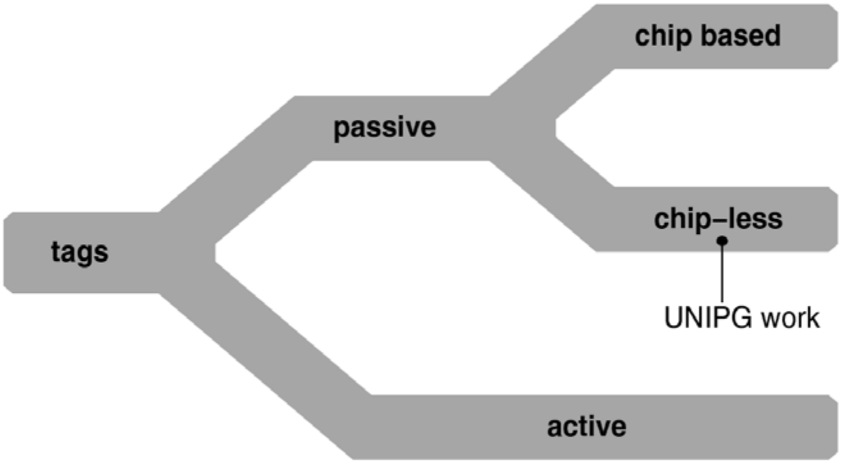
- **2 external components**.
- f_0=1.04GHz, 10% bandwidth.



P_{TX}=0 dBm; G_1=4.9dBi; G_2=4.3 dBi



Chip-less RFID tags

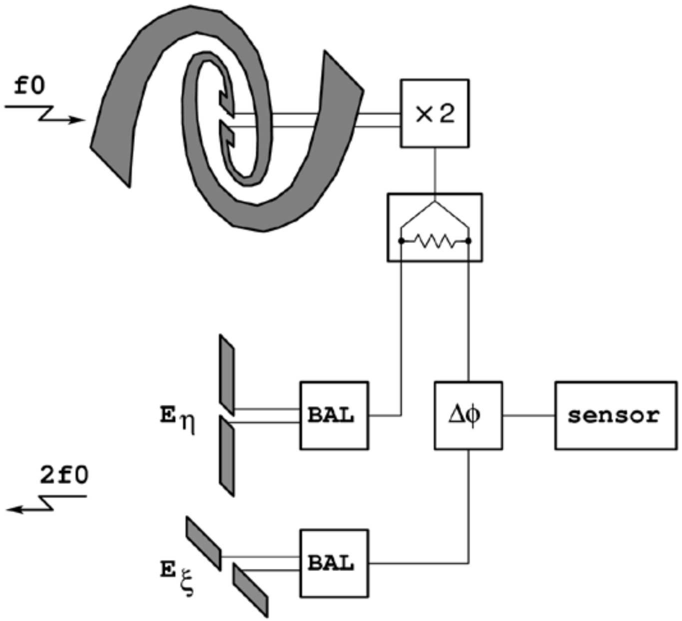


•Chip-less RFID tag are particularly simple and suitable to be implemented in cellulose-based materials.

•**How to encode sensor information ?**

Novel harmonic RFID sensor

- ***f_0*:** received by an antenna insensitive to rotation
- ***$2f_0$*:** generated by a diode circuit and split
- **First component:** transmitted in vertical polarization
- **Second component:** transmitted in horizontal polarization after a phase shifting
- **Phase shifting:** determined by the sensor
- **IQ demodulator** at reader level recover information
- No digital modulation is required to transmit information



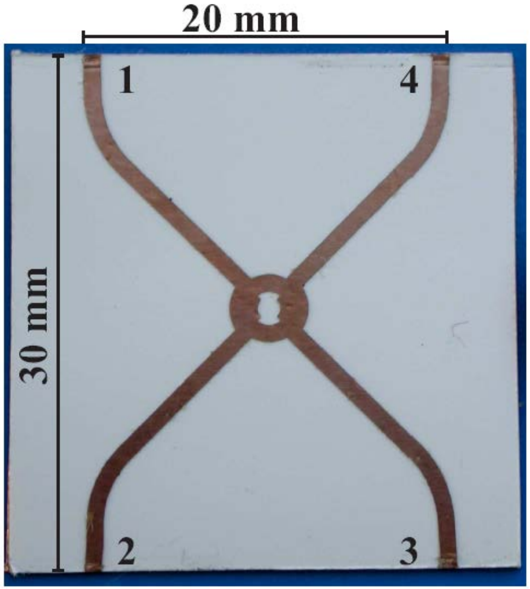
After **F. Alimenti, L. Roselli,** European Patent EP13161946.2

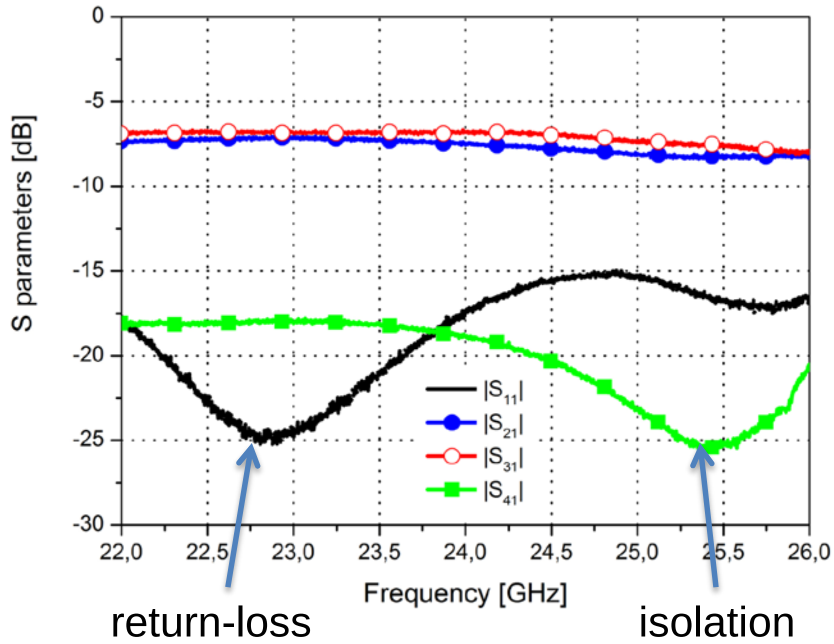
F. Alimenti and L. Roselli, "Theory of Zero-Power RFID Sensors Based on Harmonic Generation and Orthogonally Polarized Antennas," Electromagn. WAVES, vol. 134, pp. 337–357, 2013.

Millimeter-wave circuits and systems on paper…

are they possible?

24 GHz power divider



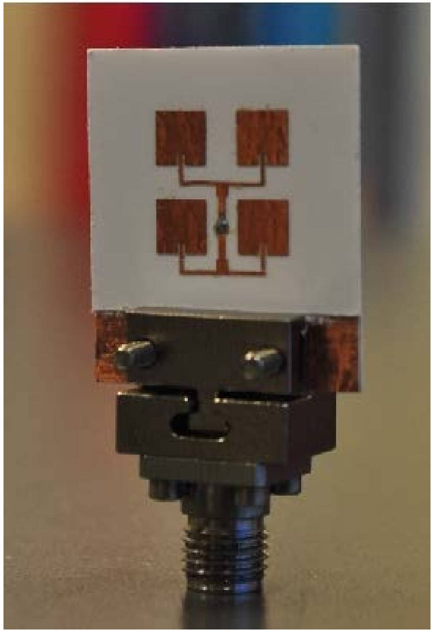


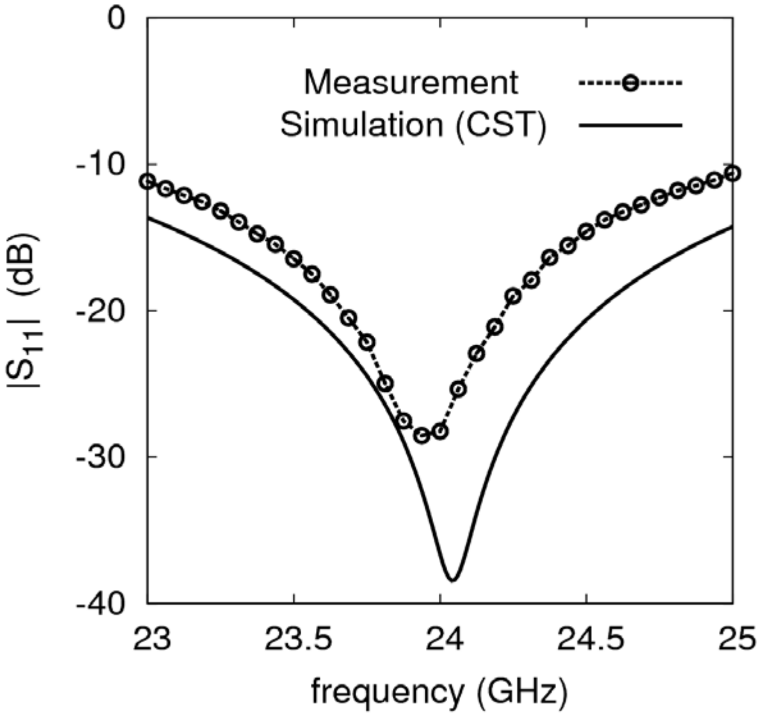
Features:

- Branch-line architecture.
- **Coupling**: 4.1 dB (after removing the insertion losses of the feeding lines).
- **Return loss**: 17 dB.
- **Isolation**: 18 dB.

C. Mariotti, F. Alimenti, P. Mezzanotte, M. Dionigi, M. Virili, S. Giacomucci, and L. Roselli, “Modeling and Characterization of Copper Tape Microstrips on Paper Substrate and Application to 24 GHz Branch-Line Couplers,” in Proceedings of European Microwave Conference (EuMC), 2013, pp. 794–797.

24 GHz patch antenna (1/2)



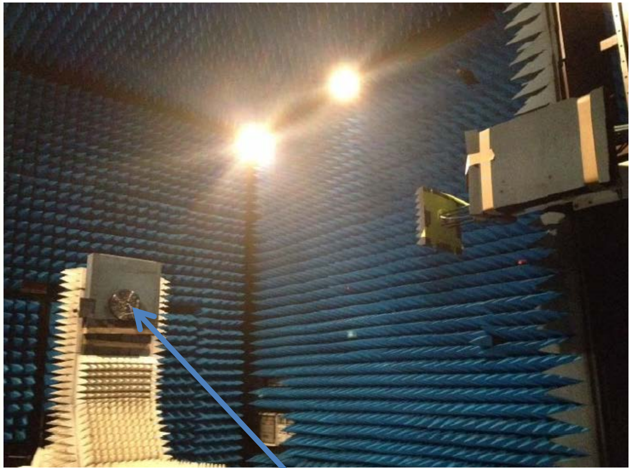


Features

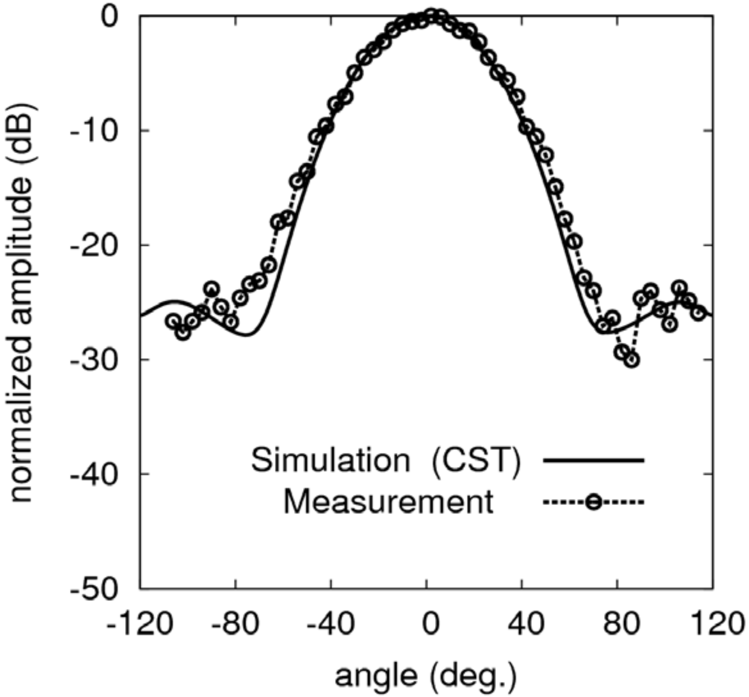
•4-patch array with equal amplitude & in-phase excitation.
•Exploits a multi-layer structure (feeding line on the other side).
•**Record frequency for similar structures on cellulose.**

V. Poggiani, F. Alimenti, P. Mezzanotte, C. Mariotti, M. Virili, G. Orecchini and L. Roselli, "24-GHz Patch antenna array on cellulose-based materials for green wireless internet applications," accepted for publication on IET 2014.

24 GHz patch antenna (2/2)



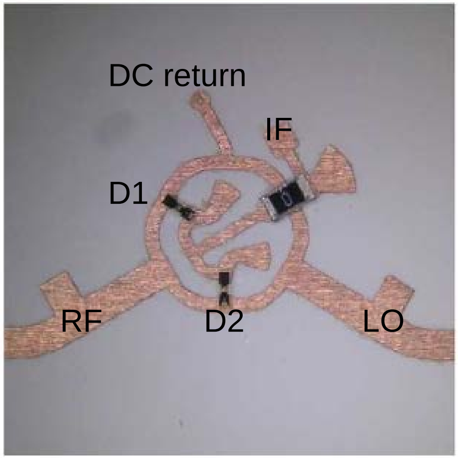
rotor with
Antenna Under Test

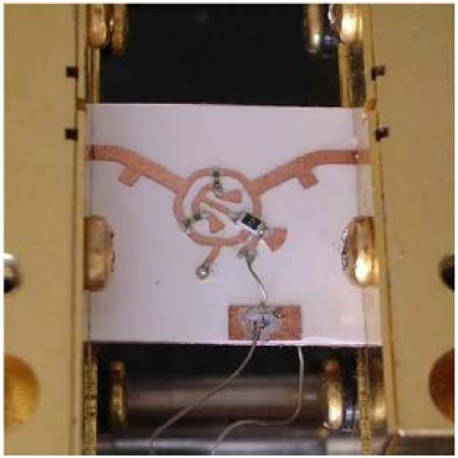


- **Half-Power Beam Width**: 48° .
- **Gain**: 7.4 dBi @ 24.15 GHz.
- **Efficiency**: 35%.
- **In just the size of a stamp**

Kindly from **Thales-Alenia Space**, Rome, Italy

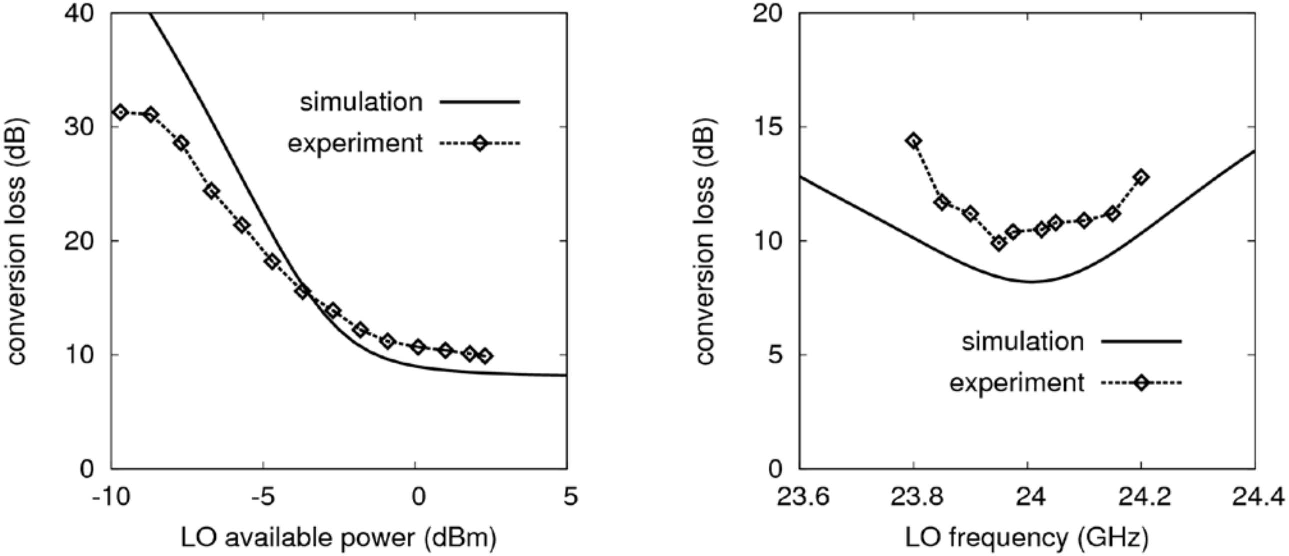
24 GHz Shottky diode mixer (1/2)





- Rat-race perimeter 3 $\lambda/2$
- Rat-race diameter 4.6 mm
- IF 0-150 MHz

24 GHz Shottky diode mixer (2/2)

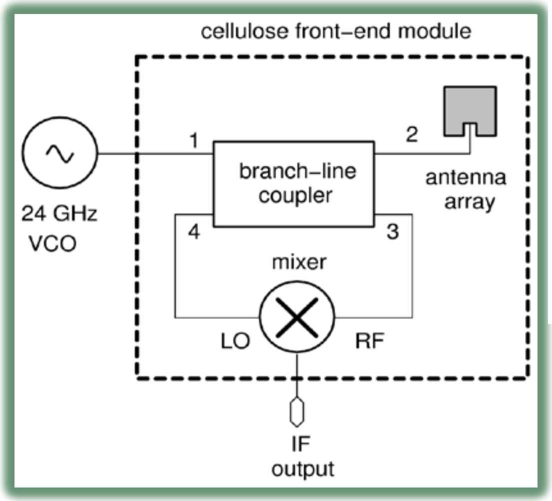


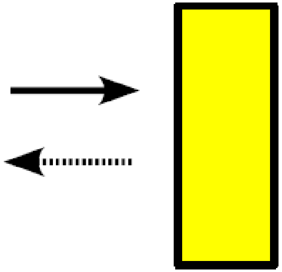
Features:
- Singly-balanced mixer.
- Rat-race 180◦ microstrip hybrid.
- Low-barrier Schottky diodes.
- **Coversion loss**: 11 dB @ 0dBm LO power.
- **Record frequency for similar circuits on cellulose**

F. Alimenti, P. Mezzanotte, S. Giacomucci, M. Dionigi, C. Mariotti, M. Virili and L. Roselli, “24 GHz Single-Balanced Diode Mixer Exploiting Cellulose-Based Materials,” IEEE Microw. Wirel. Components Lett., vol. 23, no. 11, pp. 596–598, 2013.

Let’s put everything together!

24 GHz doppler radar (1/4)



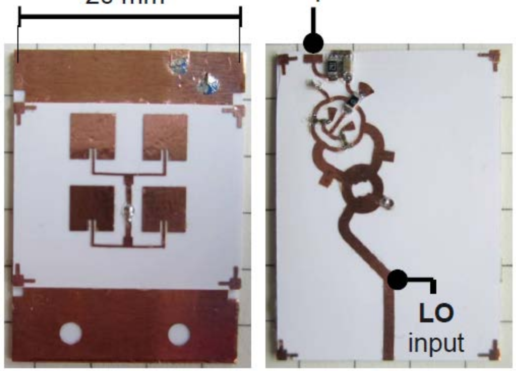


moving target (radial velocity **v**)

$$\boxed{f_\delta = f_0 \frac{2v}{c_0}}$$

Doppler shift 160 Hz per m/s @ 24 GHz

True 24-GHz multi-layer circuit on cellulose

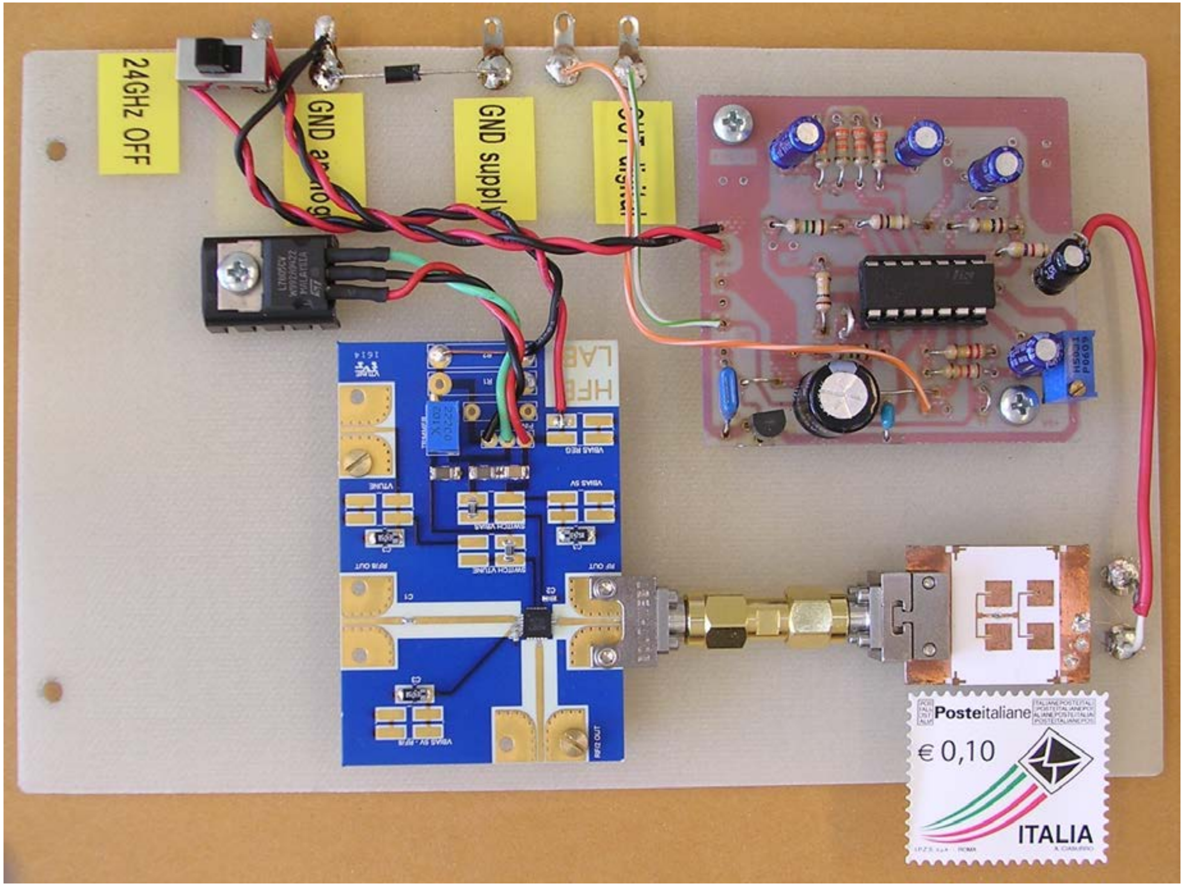


top side

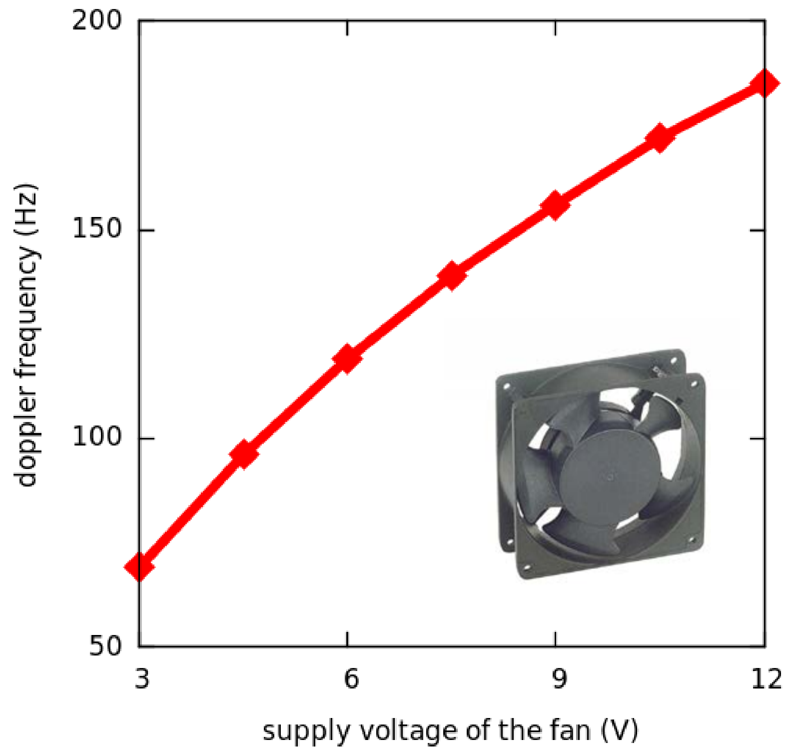
bottom side

F. Alimenti, P. Mezzanotte, C. Mariotti, M. Virili, G. Orecchini, S. Giacomucci, M. Poggiani, M. Silvestri, A. Minieri and L. Roselli, "Ultra-low-cost 24 GHz Doppler radars on cellulose-based materials: a green-electronic movement sensor for home and building automation" Submitted to IEEE Industrial Informatics Transaction, 2014.

24 GHz doppler radar (2/4)



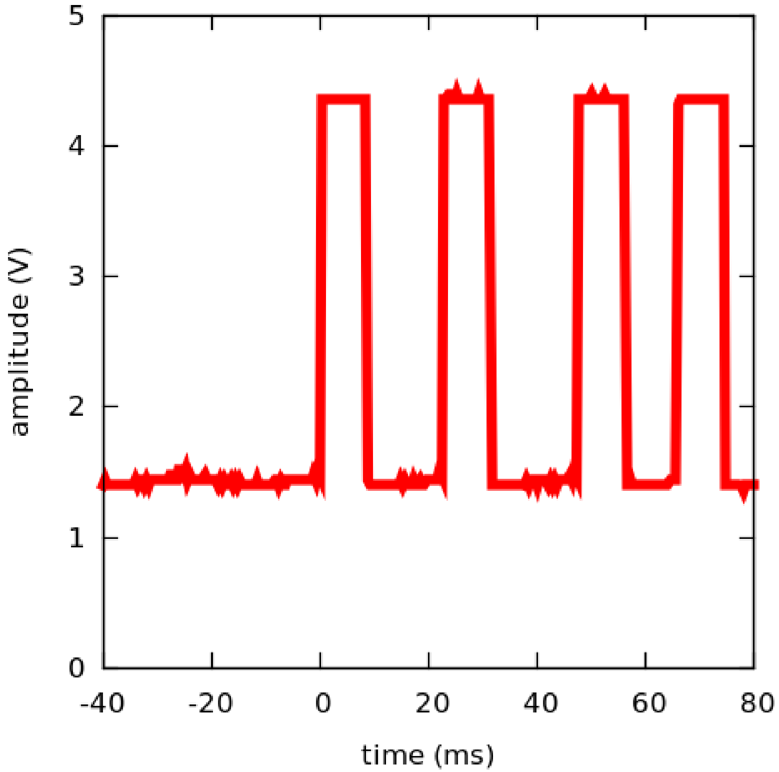
24 GHz doppler radar (3/4)



•**Moving target**: the blades of a fan at **30 cm** distance.

•**Increasing the supply voltage** of the fan (DC) motor the **Doppler frequency also increases** ...

24 GHz doppler radar (4/4)

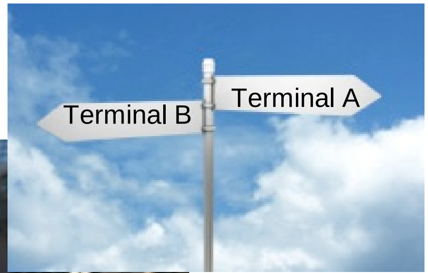


- **Moving target**: a person at **3.4 m** distance entering in a room.
- A **velocity of about 0.3 m/s** is easily detected

Prospective applications

“Smart path”

Where am I?

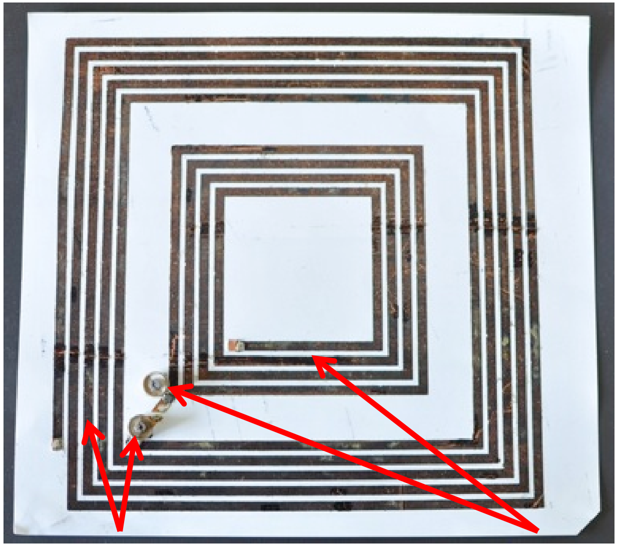


Technological layers:

- Wireless comm. to the web (optional)
- Personal information Sys
- Nomadic Reader
- Tag embedded in the floor

Organic harmonic tag

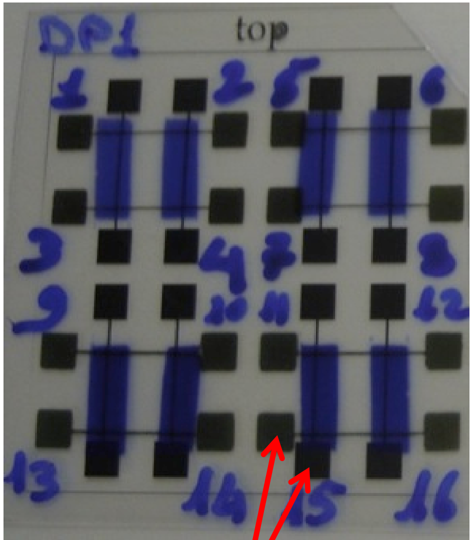
Frequency doubler



Inductor and capacitor of the resonator @ f_0

Inductor and capacitor of the resonator @ $2f_0$

Organic diodes



Metallic contacts of a single diode

M. Virili, G. Casula, C. Mariotti, G. Orecchini, F. Alimenti, P. Mezzanotte, A. Bonfiglio and L. Roselli, “7.5-15 MHz Organic Frequency Doubler Made with Pentacene-Based Diode and Paper Substrate,” in IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST, 2014.

“Smart surface” concept

Proceedings OF THE IEEE

Special Issue on:
“Energy Harvesting and Scavenging”

December 2014

L. Roselli, N. B. Carvalho, F. Alimenti, P. Mezzanotte, G. Orecchini, M. Virili, C. Mariotti, R. Goncalves and P. Pinho, “**Smart Surfaces: Large Area Electronics systems for Internet of Things enabled by Energy Harvesting**”, To appear, December 2014.

Final considerations

CONSORZIO NAZIONALE INTERUNIVERSITARIO
PER LA NANOELETTRONICA

PROGRAMMA DELLA GIORNATA IU.NET

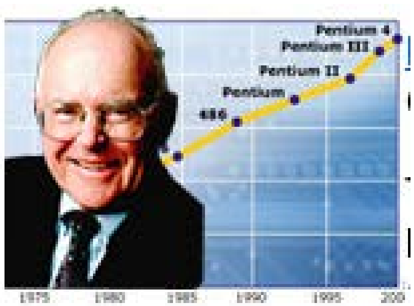
10:30 Luca Selmi: Attività IUNET nell'area "More Moore"

11:10 Andrea Lacaita: Attività IUNET nell'area "More than Moore"

11:50 Giuseppe Iannaccone: Attività IUNET nell'area "Beyond CMOS"

Final cosnsiderations

"It [Moore’s law] can't continue forever. The nature of exponentials is that you push them out and eventually disaster happens.”

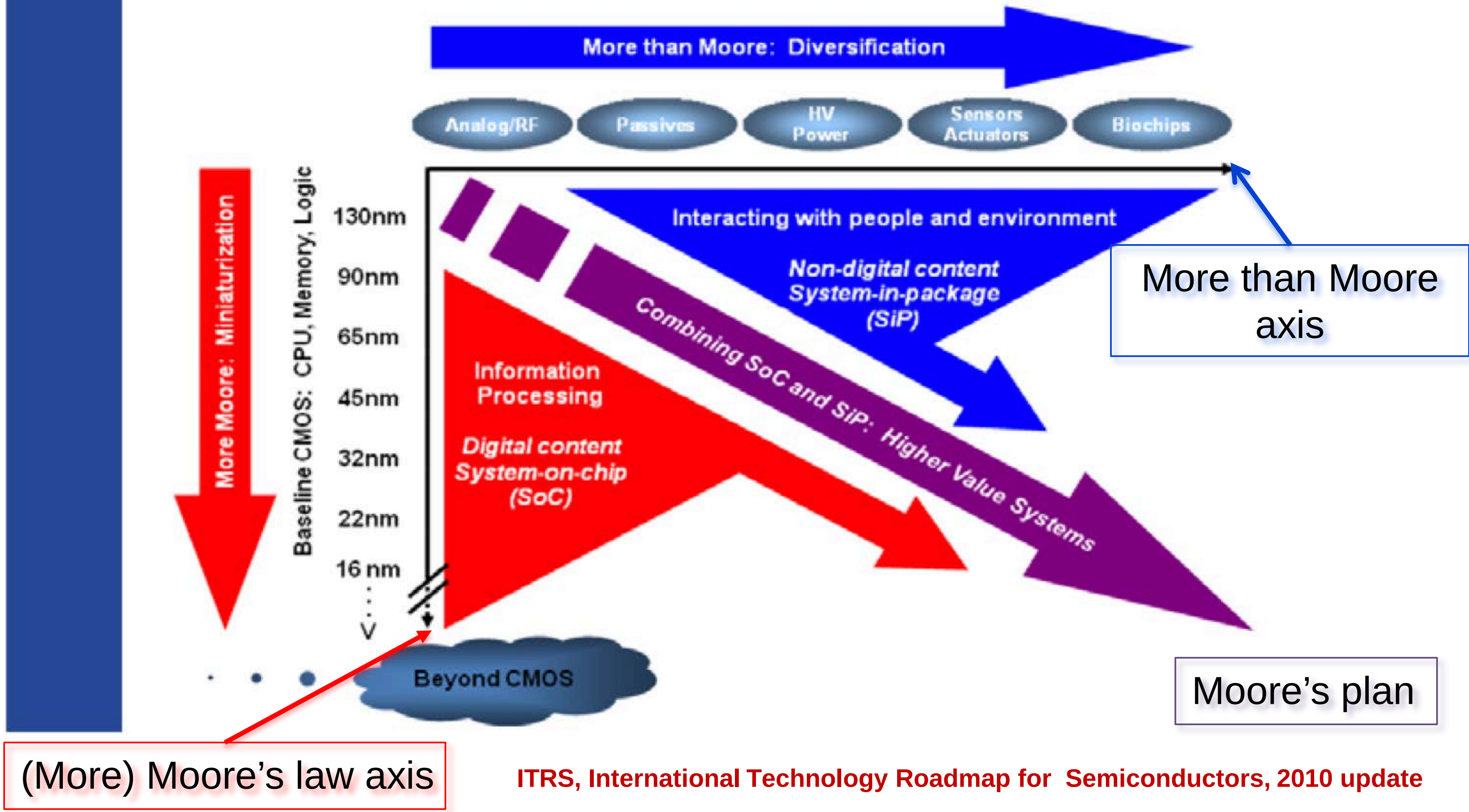


Gordon Moore

In an intervew to celebrate 40 years since the formulation of his law

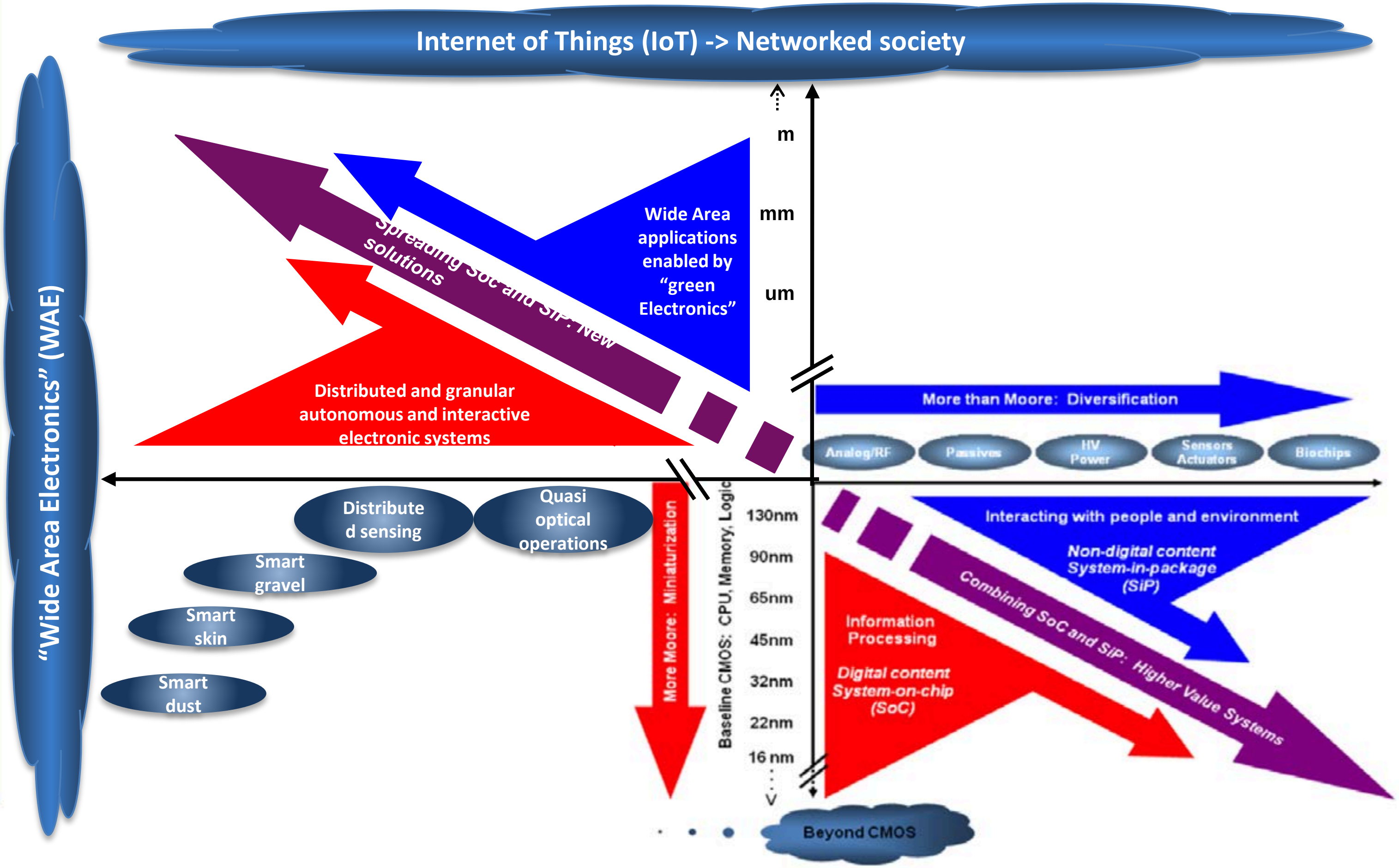
April 13, 2005

Final considerations

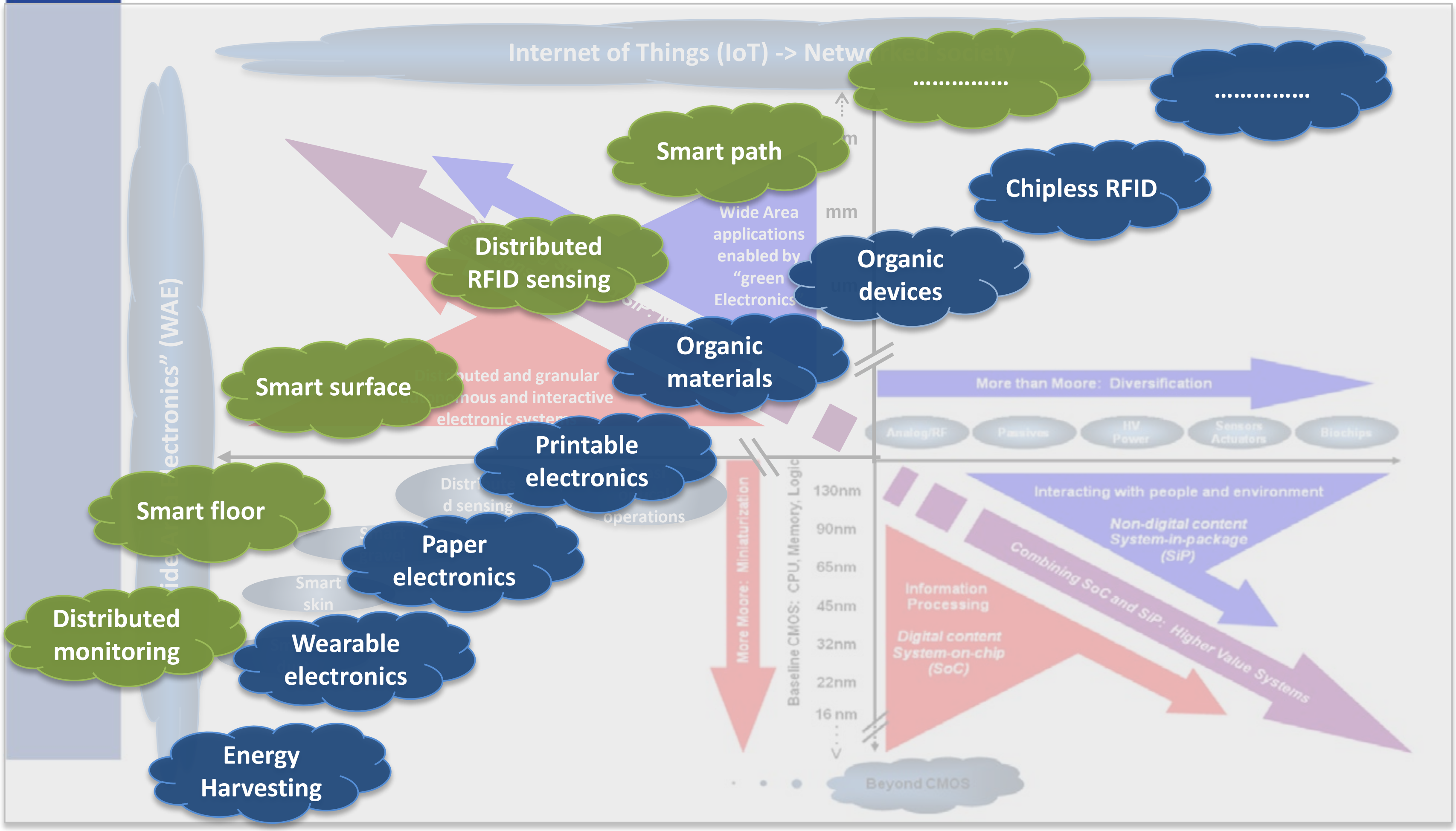


ITRS, International Technology Roadmap for Semiconductors, 2010 update

Final considerations



Final considerations



Closing sentence

Instead of bringing paper to electronics let's bring electronics to paper

Thank you and to the beautiful HFE-LAB team

Prof. Luca Roselli

Prof. Paolo Mezzanotte

Prof. Federico Alimenti

Ing. Giulia Orecchini (Post-doc)

Ing. Marco Virili (Ph.D. Student)

Ing. Chiara Mariotti (Ph.D. Student)

UNIVERSITÀ DEGLI STUDI DI PERUGIA

Thank you!

HF lab