Micro- and millimeter-wave electronic circuits on cellulose substrates: promising means for the development of the IoT physical layer
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
- Passives
  - Recyclable, biodegradable materials
- Actives
  - Organic Devices

Energetically autonomous
- Low power
- Wireless Power Transfer (WPT) and Energy Harvesting (EH)
Technologies and materials

- OLED
- OTFT
- OSM
- Graphene
- Paper
- Bioplastic
- PET
RF circuits on cellulose: UNIPG-HFE developments
“Some bricks in the wall”
Ink-jet printed RF electronics

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

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 yield variations of the backscattered power level

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

Adhesive copper laminate (2/2)

Technology features:
• 35 μm thick solid copper ($\sigma = 5.8 \times 10^8$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>900 μm</td>
</tr>
<tr>
<td>$h$</td>
<td>250 μm</td>
</tr>
<tr>
<td>$t_a$</td>
<td>30 μm</td>
</tr>
<tr>
<td>$t_m$</td>
<td>35 μm</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>3.2</td>
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<tr>
<td>$\tan \delta$</td>
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<tr>
<td>$\varepsilon_{r,a}$</td>
<td>1.3</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>$5.8 \times 10^7$ S/m</td>
</tr>
</tbody>
</table>

Parameter | Value  |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\varepsilon_r$(eq)</td>
<td>2.55</td>
</tr>
<tr>
<td>$\tan \delta$(eq)</td>
<td>0.05</td>
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<tr>
<td>$h$(eq)</td>
<td>370 μm</td>
</tr>
</tbody>
</table>

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.
- $f_0=998$ MHz.
- -20 dBm output power.
- **0.9 mW @ 1.2 V supply**

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 $f_0$ (fundamental).
- The tag contains a frequency multiplier (typically a frequency doubler) and answers at $n \times f_0$ (for a doubler at $2 \times f_0$).
- 1-bit RFID system (it can determine the presence of the tag)
- it is insensitive to the environment backscattering
Crossed-dipole tag

\[ f_0 = 3.5 \text{ GHz} \quad 2f_0 = 7 \text{ GHz} \]


Microstrip frequency doubler

\[ f_0 = 1.04 \text{ GHz} \]
\[ 2f_0 = 2.08 \text{ GHz} \]

- Low-barrier Schottky diode (HSMS 2850).
- Input & output harmonic terminations implemented with \( \lambda/4 \) stubs.
- IMN: tapped impedance transformer.
- OMN: optimized by load-pull simulations.

**Minimum component count → suitable for harmonic RFID tags on cellulose**

Microstrip frequency doubler (2/2)

Features:
• 2 external components.
• \( f_0 = 1.04 \text{GHz}, 10\% \) bandwidth.

\[ P_{TX} = 0 \text{ dBm}; \ G_1 = 4.9 \text{dBi}; \ G_2 = 4.3 \text{ dBi} \]
Chip-less RFID tags

- Chip-less RFID tags 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

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

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.

• **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 λ/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.
• Conversion loss: 11 dB @ 0dBm LO power.
• Record frequency for similar circuits on cellulose

Let’s put everything together!
24 GHz doppler radar (1/4)

Doppler shift: $f_\delta = f_0 \frac{2v}{c_0}$

Moving target (radial velocity $v$)

True 24-GHz multi-layer circuit on cellulose

24 GHz doppler radar (2/4)
• **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** ...
• 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

“Smart surface” concept

Special Issue on:
“Energy Harvesting and Scavenging”

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”
"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 interview 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

Internet of Things (IoT) -> Networked society

Distributed and granular autonomous and interactive electronic systems

Wide Area applications enabled by “green Electronics”

Spreading SoC and SiP: New solutions

Distribute d sensing

Quasi optical operations

Smart gravel

Smart skin

Smart dust

“Wide Area Electronics” (WAE)

Baseline CMOS: CPU, Memory, Logic

Beyond CMOS

More Moore: Miniaturization

Combining SoC and SiP: Higher Value Systems

Non-digital content System-in-package (SIP)

Interacting with people and environment

Information Processing

Digital content SoC and SiP: Higher Value Systems

More than Moore: Diversification

Analog/RF

Passives

HV Power

Sensors

Actuators

Biochips

Wide Area Electronics (WAE)
Final considerations

- Smart dust
- Smart gravel
- Smart skin
- Distributed sensing
- Wide Area applications enabled by “green Electronics”
- Distributed and granular autonomous and interactive electronic systems
- Internet of Things (IoT) -> Networked society
- Organic devices
- Chipless RFID
- Wide Area Electronics (WAE)
- Distributed RFID sensing
- Smart path
- Organic materials
- Printable electronics
- Paper electronics
- Wearable electronics
- Energy Harvesting
- Smart floor
- Smart surface
- Distributed monitoring
- More than Moore: Diversification
- Analog/RF
- Passive
- HV Power
- Sensors
- Smart skin
- More Moore: Miniaturization
- Baseline CMOS: CPU Memory Logic
- Interacting with people and environment
- Non-digital content System-in-package (SIP)
- Information Processing
- Digital content System-on-chip (SoC)
- Combining SoC and SIP: Higher Value Systems
- Beyond CMOS
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)
Thank you!