International Spring School on
Electromagnetics and emerging technologies for pervasive applications:
Internet of Things, Health and Safety

Substrate Integrated Waveguide (SIW) Components on Paper, Textile, and 3D-Printed Substrates for the Internet of Things

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OUTLINE

PART 1 – APPLICATION: WSN AND IOT

1. Technology for the Next Generation of Wireless Systems

PART 2 – TECHNOLOGY: SUBSTRATE INTEGRATED WAVEGUIDE

2. Substrate Integrated Waveguide (SIW) Technology

3. SIW Components and Antennas

PART 3 – NEW MATERIALS: PAPER, TEXTILE, 3D-PRINTING

4. Paper-based Substrate Integrated Waveguide

5. Wearable SIW Structures on Textile

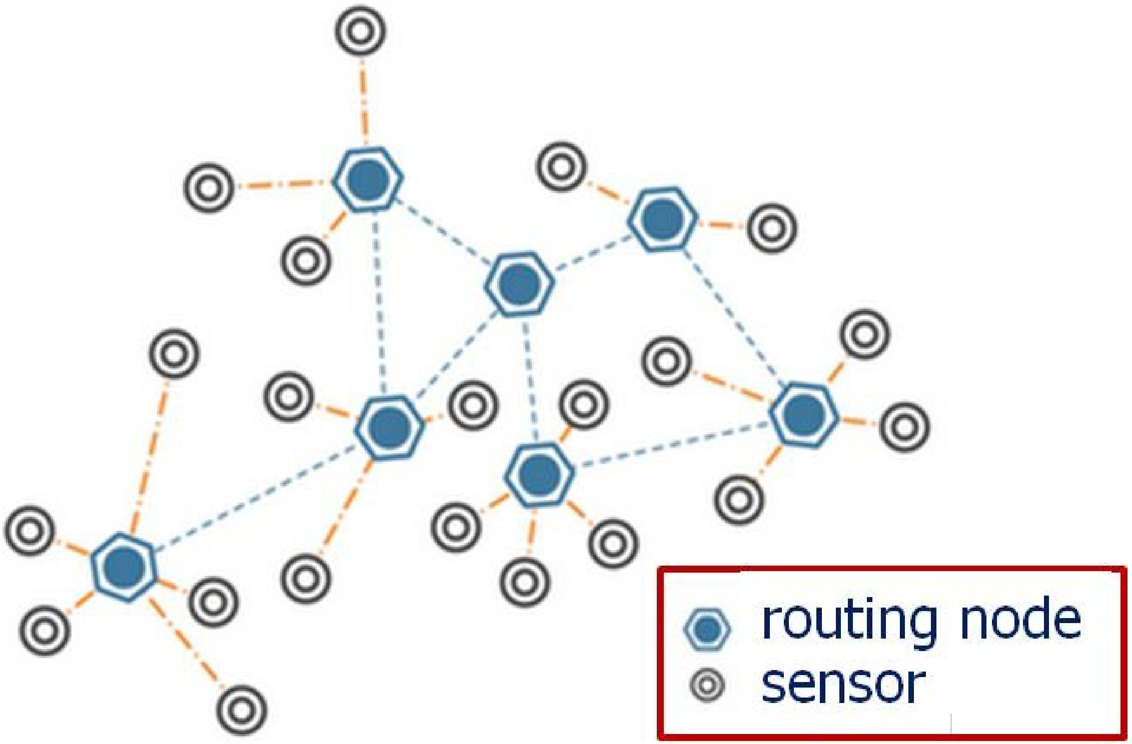
6. 3D-Printing of Microwave Components

Part 1 – Application:

WSN and IOT

WIRELESS SENSOR NETWORKS

A wireless sensor network (WSN) consists of **spatially distributed** autonomous **sensors** to **monitor physical or environmental conditions** (temperature, humidity, pressure, pollutants, …).

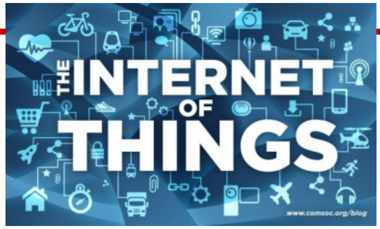


Applications:

- Remote monitoring in harsh environment
- Agriculture applications
- Monitoring of industrial processes

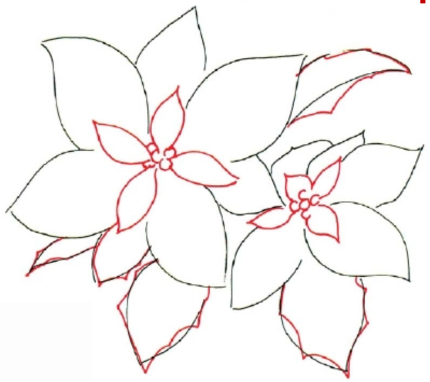
INTERNET OF THINGS (IOT)

"The next logical step in the technological revolution connecting people anytime, anywhere is to connect inanimate objects. This is the vision underlying the **Internet of things: anytime, anywhere, by anyone and anything**" – ITU, November 2005



food treatment

wake-up call



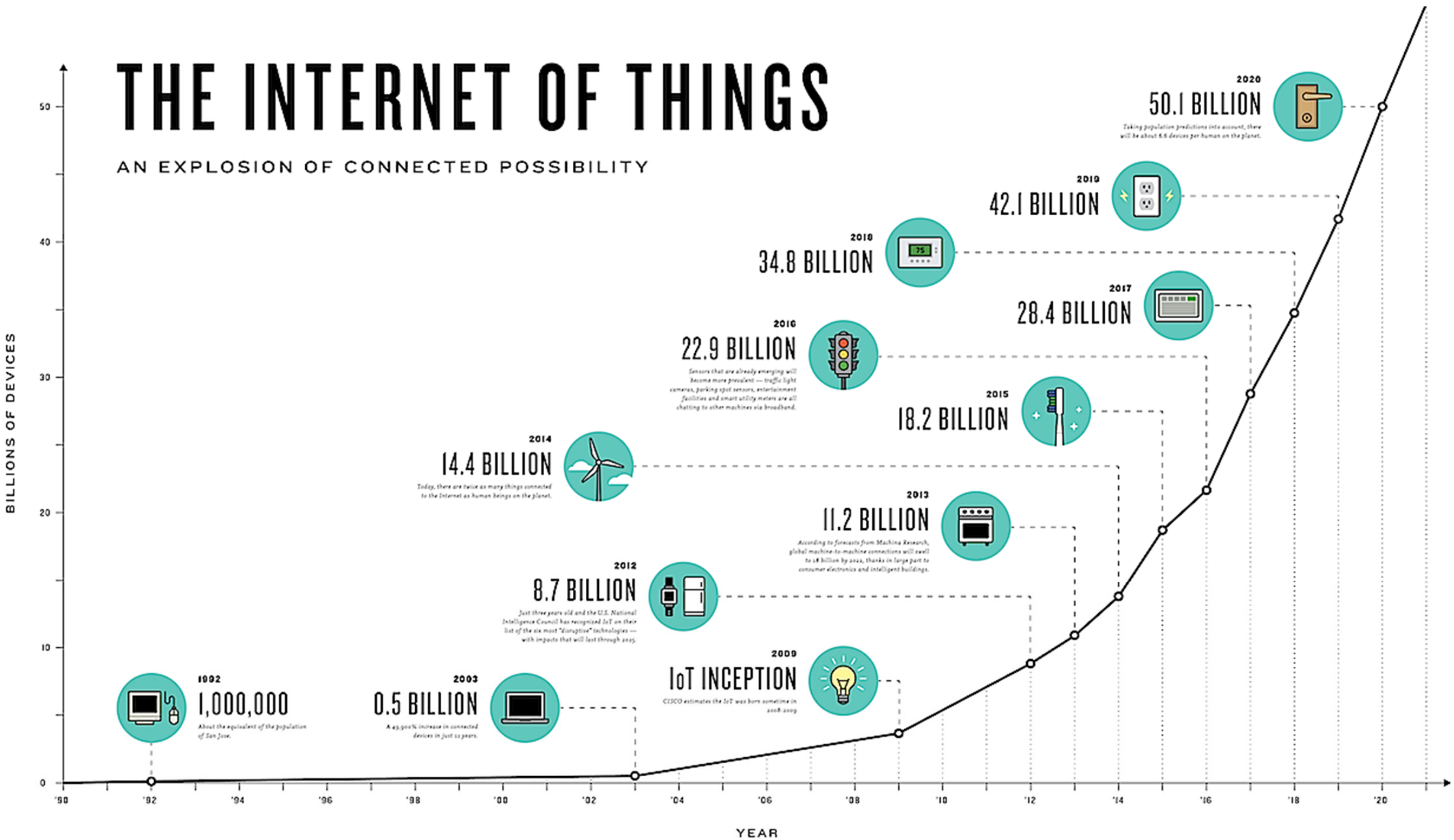
garden watering

sport

cars and transportation

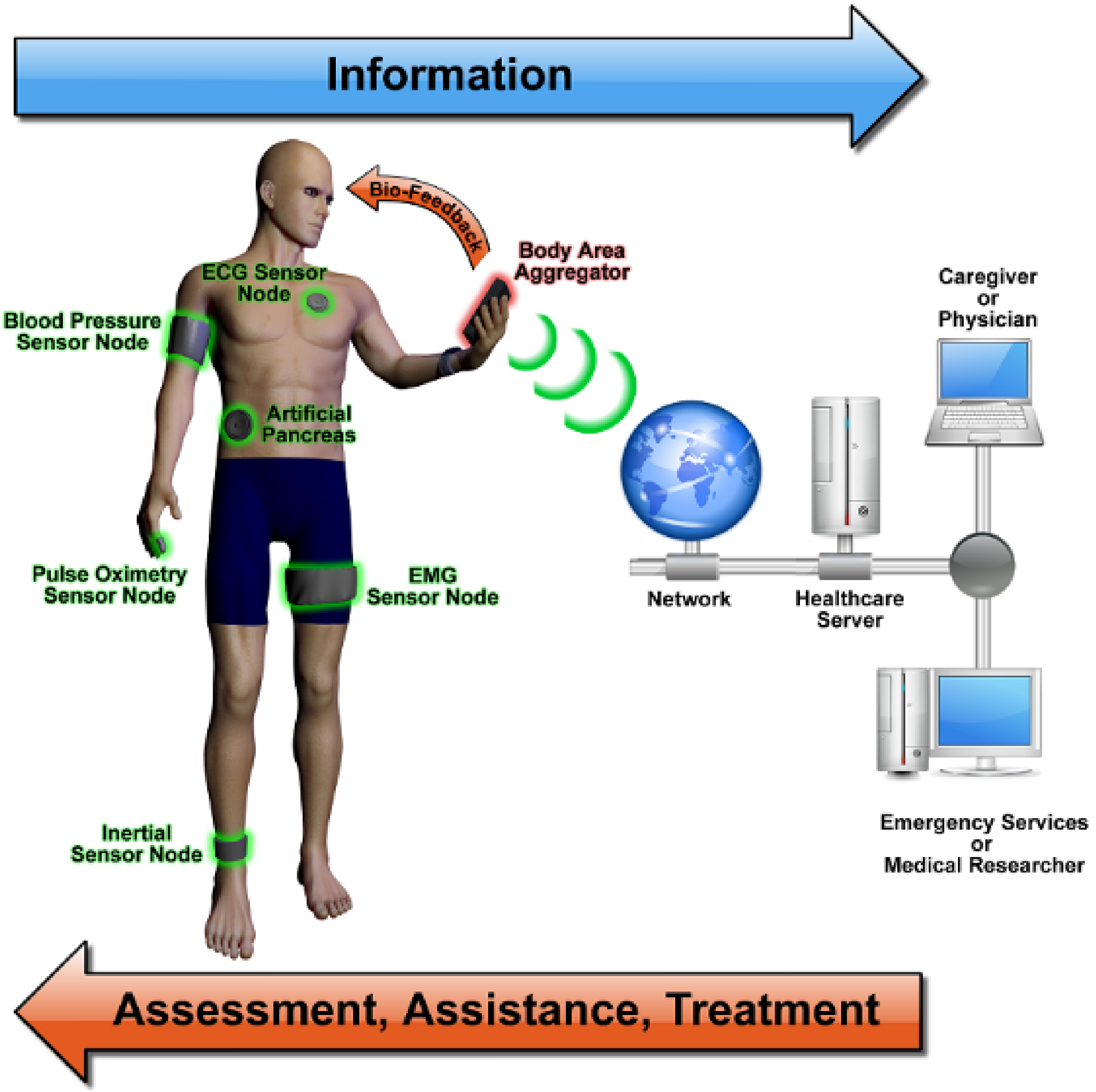
survaillance

INTERNET OF THINGS (IOT)



I-Scoop website "http://www.i-scoop.eu/internet-of-things/". Accessed Sept. 2015.

Biomedical Applications



TECHNOLOGICAL REQUIREMENTS

The key points for the development of WSN and IoT are:

- low cost
- easy integration of the complete wireless system
- minimum impact on the environment
- wearable devices
- self-powering (energy harvesting)

This leads to the selection of

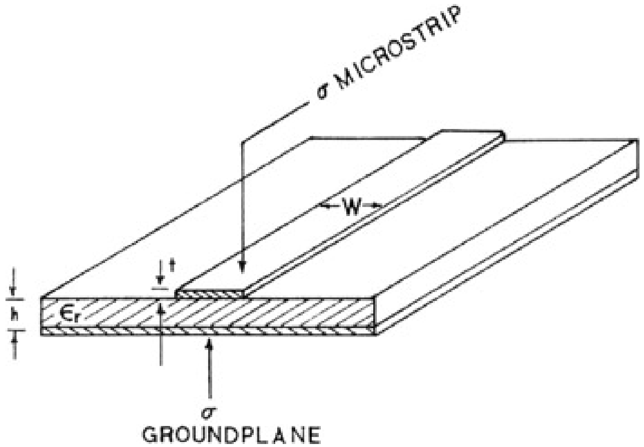
- a technology able to efficiently **integrate** active elements, passive components, and antennas
- **eco-friendly materials** and technologies

Part 2 – Technology:

Substrate Integrated Waveguide

TRADITIONAL TRANSMISSION LINES

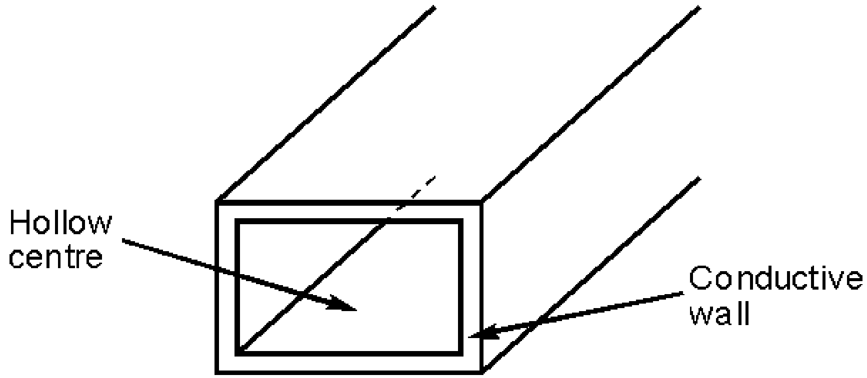
The guided wave propagation in the microwave region is preferably obtained by using microstrip lines and metallic waveguides.



MICROSTRIP LINES (planar)

- Light and compact
- Low fabrication cost
- High losses
- High cross-talk

TECHNOLOGICAL GAP

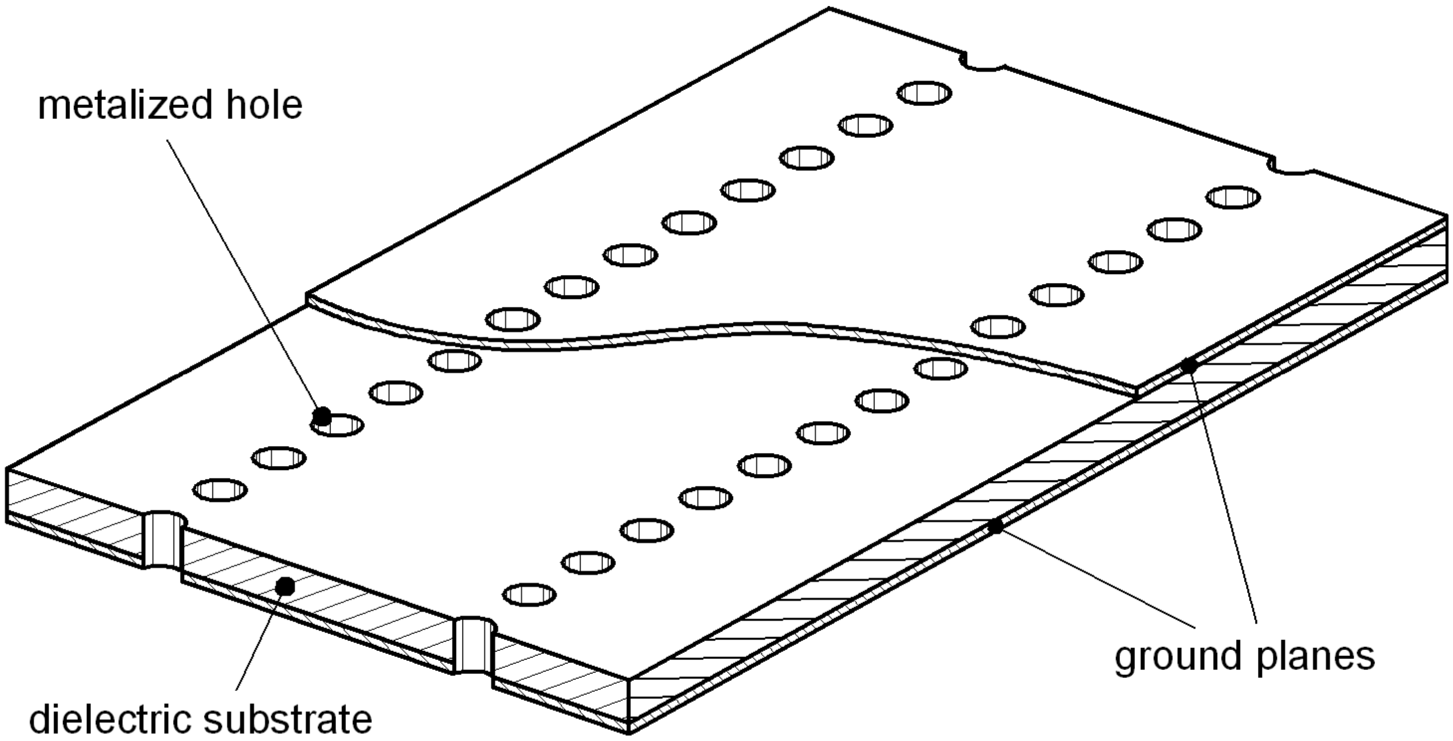


METALLIC WAVEGUIDES (non-planar)

- Low losses
- Completely shielded
- Bulky and expensive
- Difficulties with active components

SUBSTRATE INTEGRATED WAVEGUIDE

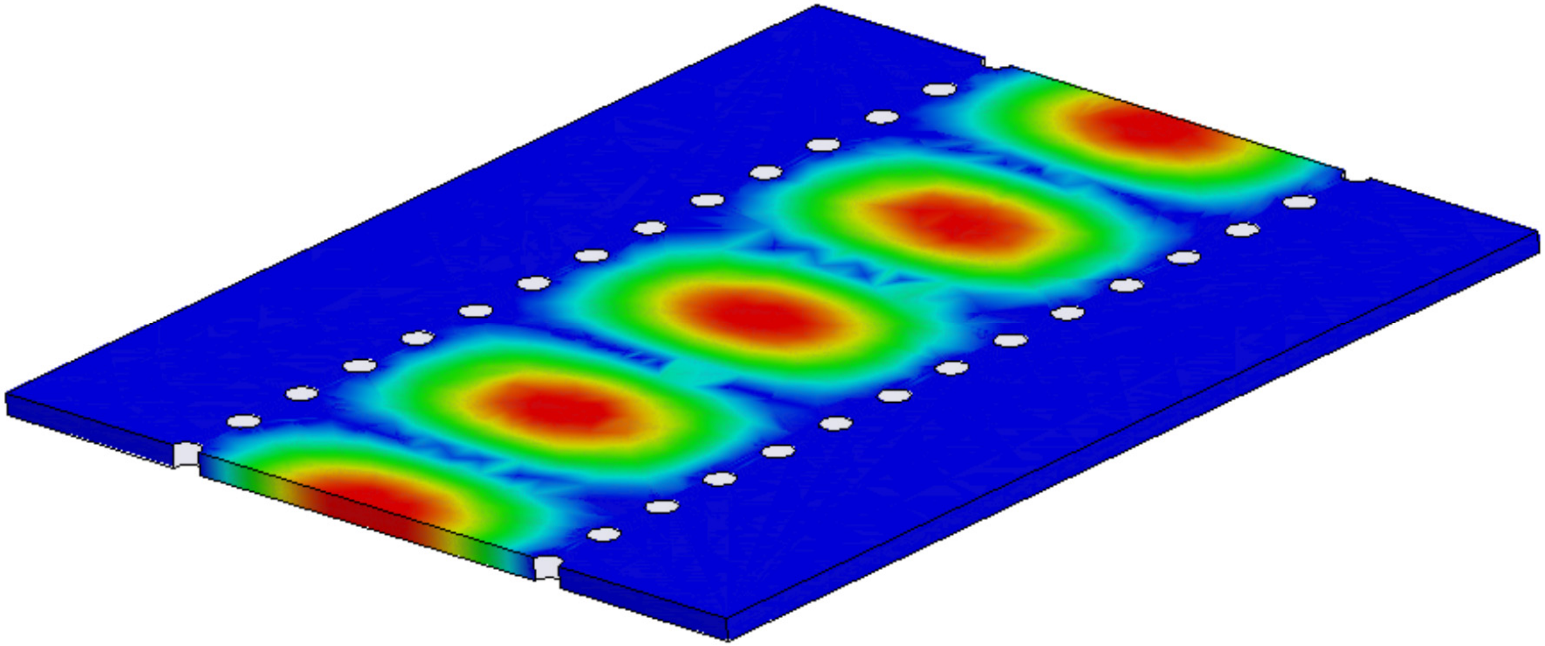
Substrate Integrated Waveguides (**SIW**) are novel transmission lines that implement rectangular waveguides in planar form.



SIW consist of two rows of conducting cylinders embedded in a dielectric substrate that connect two parallel metal plates.

SIW INTERCONNECTS

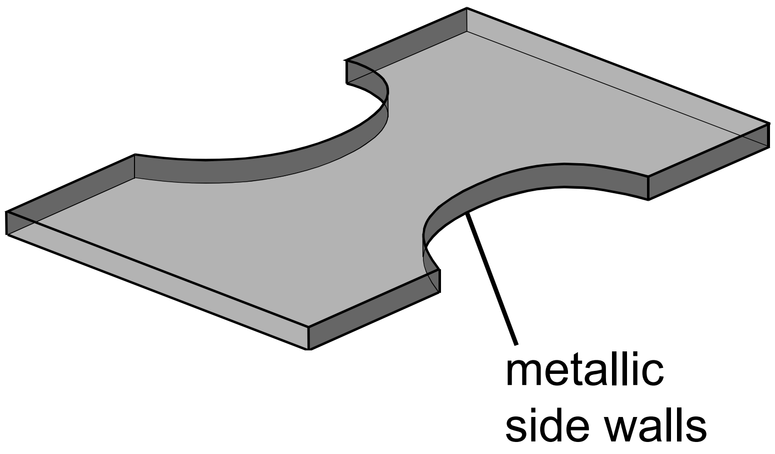
The **modal field propagation** in SIW interconnects is similar to classical rectangular waveguides.



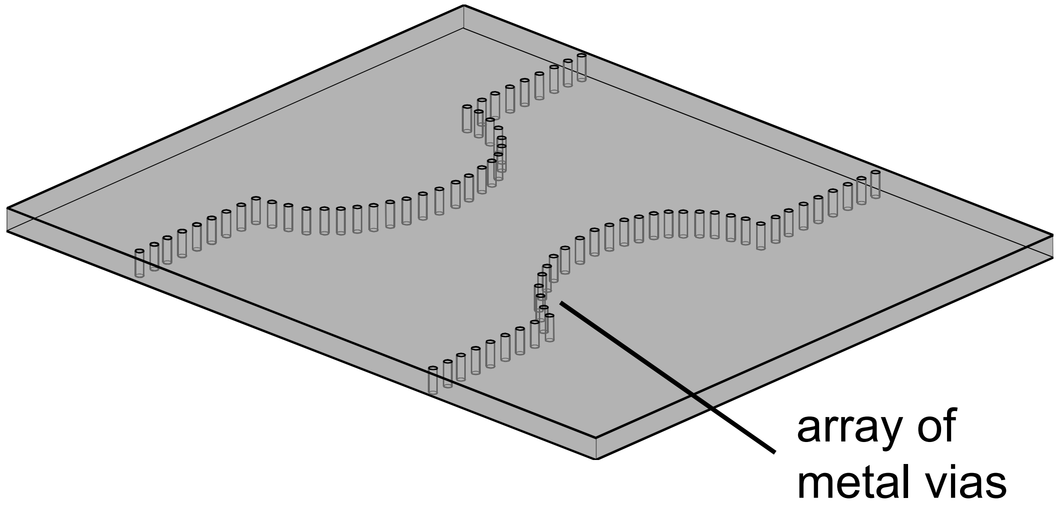
Only TE_{n0} modes (n=1, 2, …) can be supported by SIW structures.

SIW Components

SIW technology permits to realize waveguide components in a dielectric substrate by replacing the metallic side walls by arrays of metal vias.



planar waveguide component

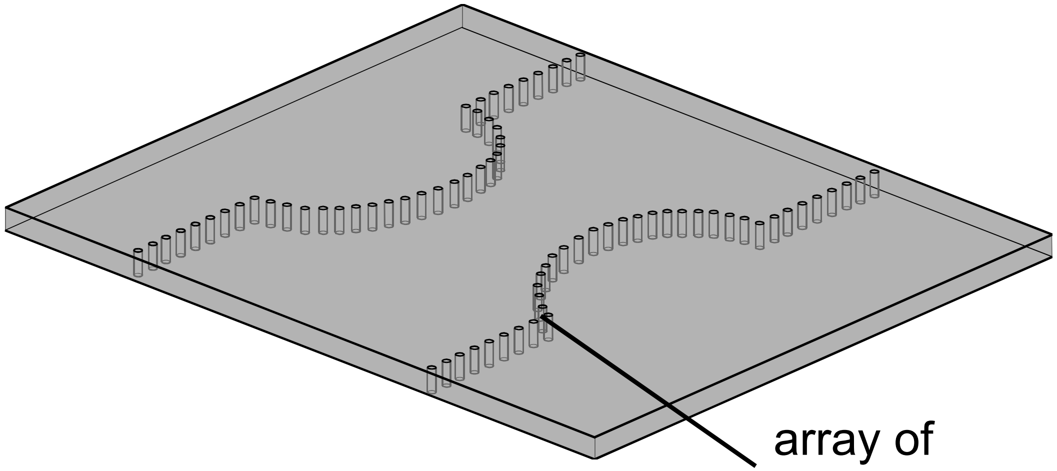


corresponding SIW component

FABRICATION OF SIW STRUCTURES

The fabrication of SIW structures is typically based on

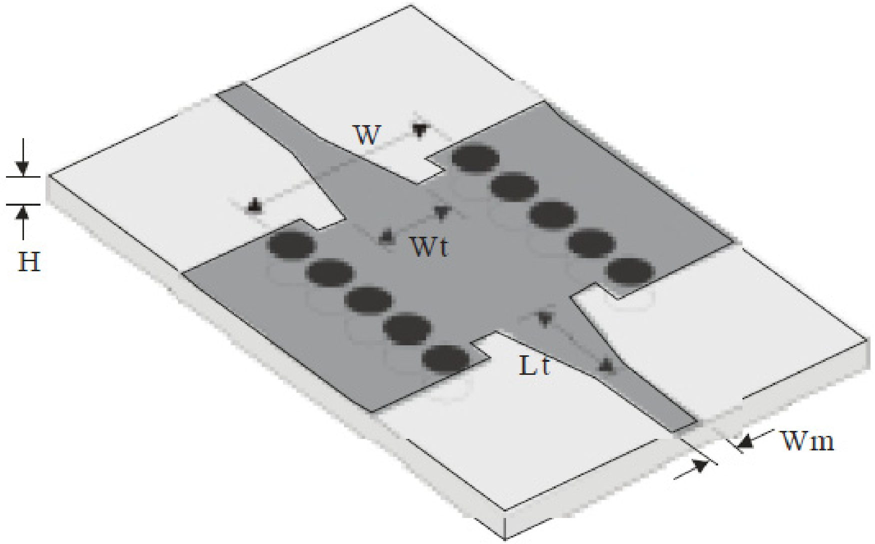
- perforation of the dielectric substrate by mechanical drilling or laser
- metallization of the holes



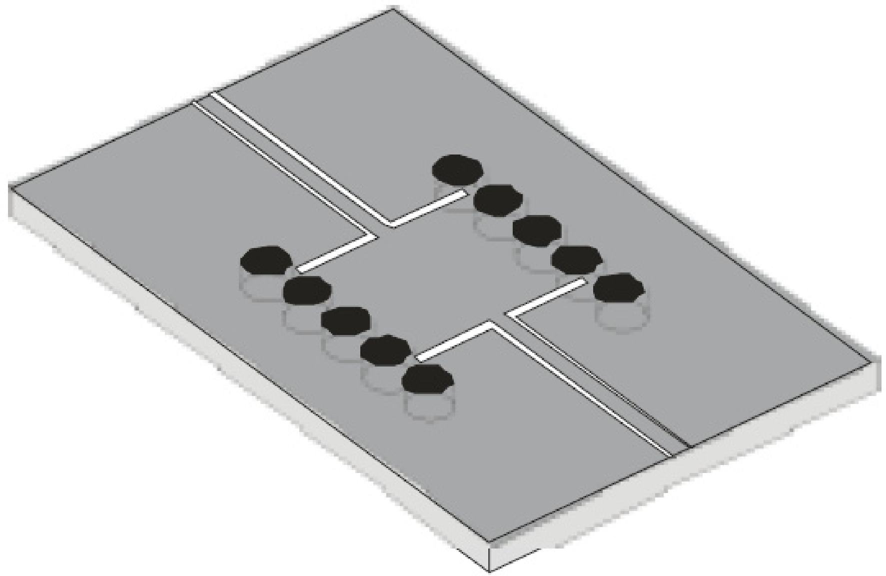
This fabrication process is **accessible** to small and medium enterprises and permits **low manufacturing costs**.

SIW TRANSITIONS

SIW structures can be easily integrated with planar transmission lines through wide-band transitions.

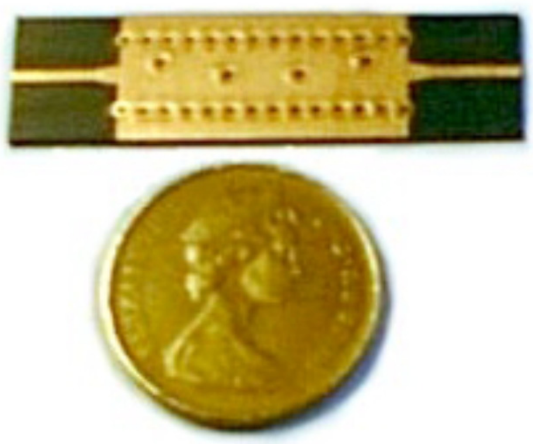


SIW-to-microstrip transition

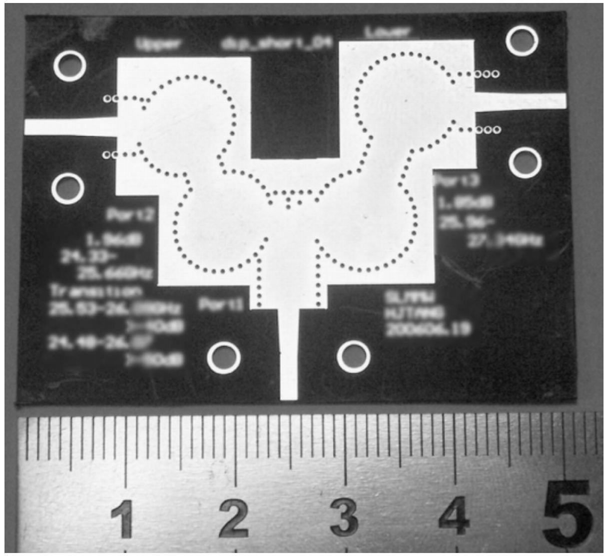


SIW-to-coplanar transition

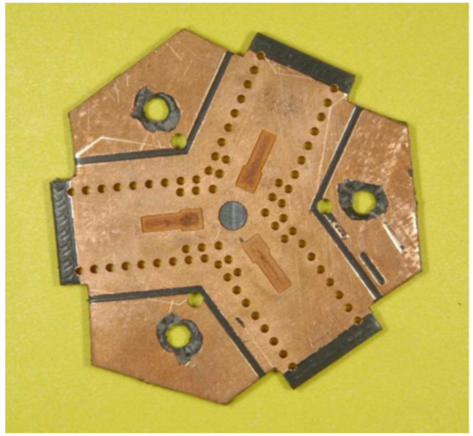
SIW Passive Components



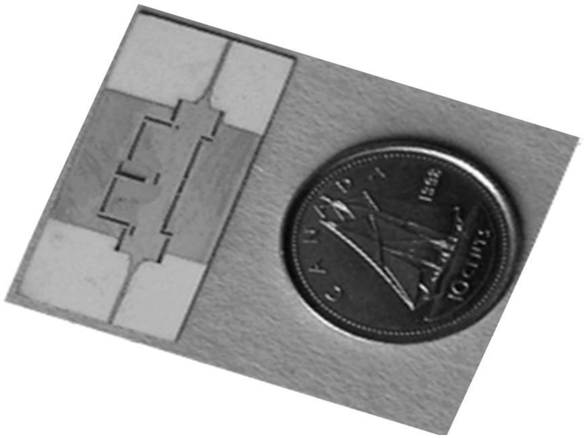
SIW post filter at 27 GHz



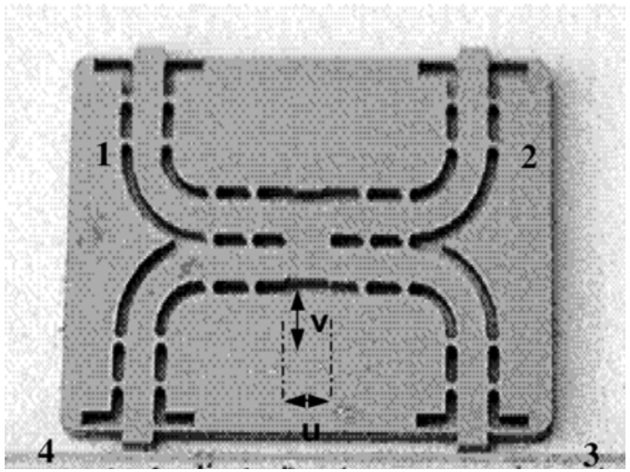
SIW diplexer at 26 GHz



SIW circulator at 24 GHz

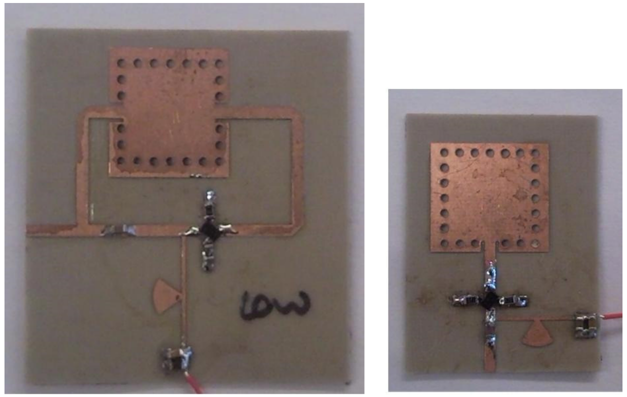


SIW dual-mode filter at 24 GHz

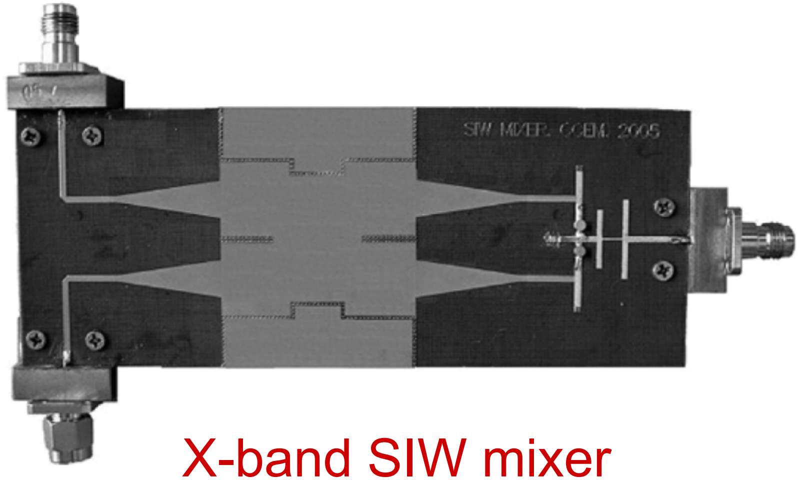


SIW hybrid coupler at 94 GHz

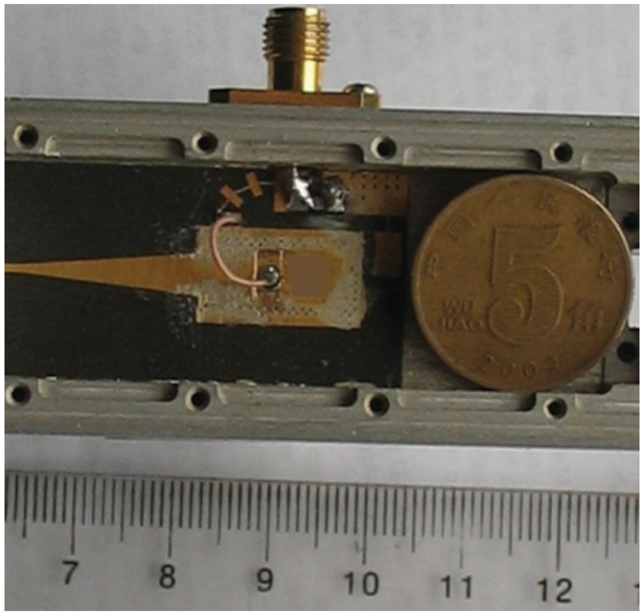
SIW ACTIVE COMPONENTS



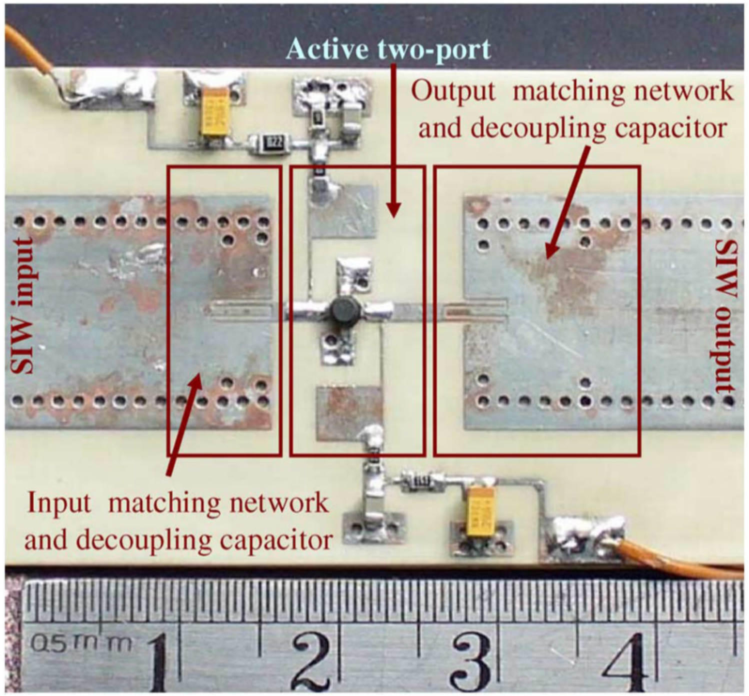
12 GHz SIW oscillators



X-band SIW mixer



SIW Gunn oscillator at 35 GHz

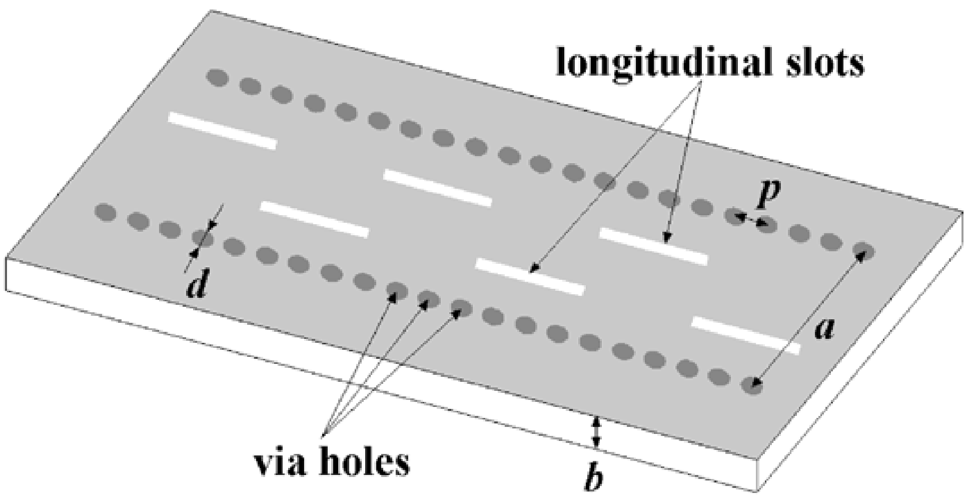


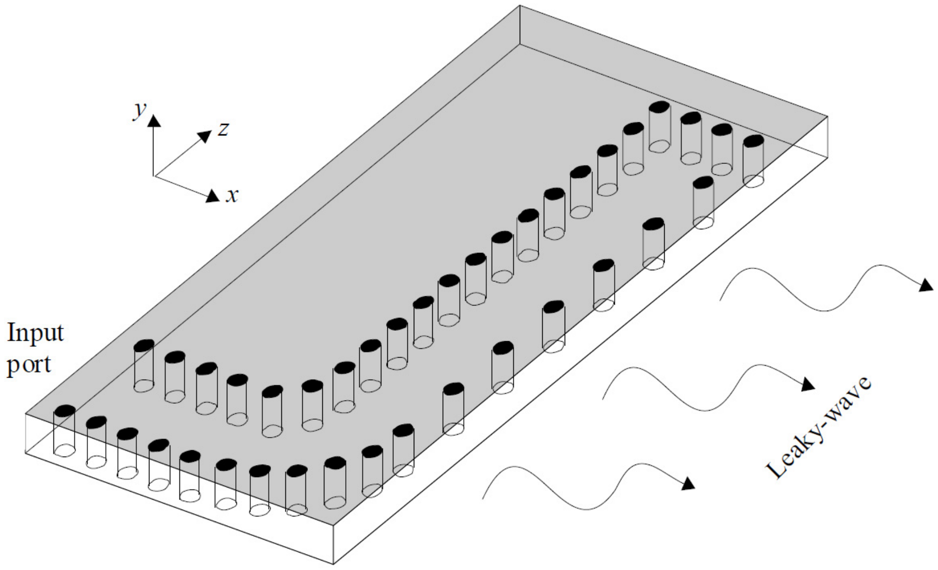
X-Band SIW amplifier

SIW ANTENNAS

There are two major topologies of SIW antennas:

- slotted waveguide antennas are based on longitudinal slots;
- leaky-wave SIW antennas, obtained by properly spacing the metal vias in order to create radiation leakage.





SYSTEMS-ON-SUBSTRATE (SOS)

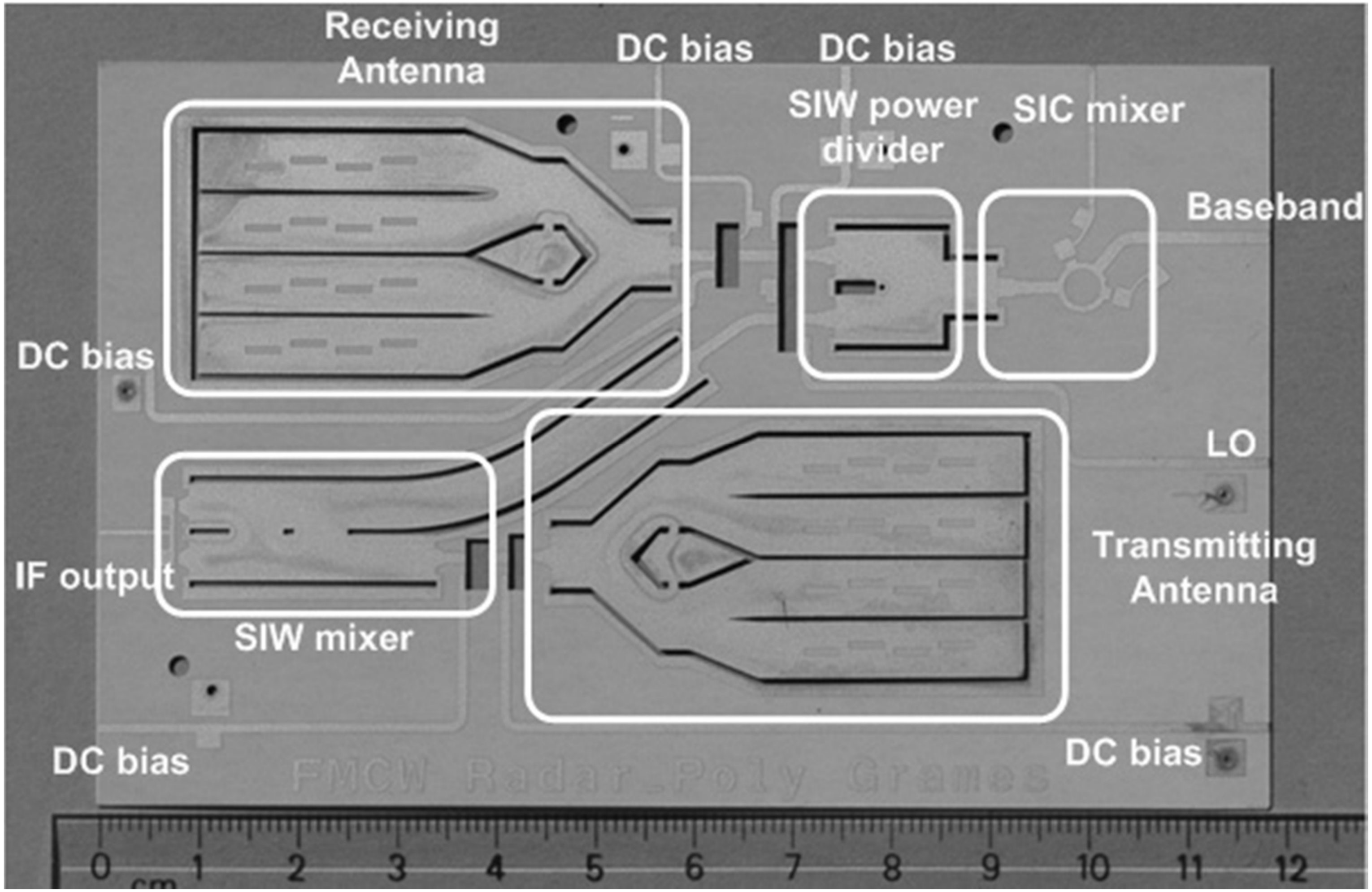
The most significant advantage of SIW technology is the possibility to **integrate all components on the same substrate**, including passive components, active elements and antennas.

- possibility to mount one or more chip-sets on the same substrate
- no need for transitions between different elements
- reduced losses and parasitics

SoS represents the ideal platform for developing cost-effective, easy-to-fabricate and high-performance mm-wave systems.

System-on-Substrate (SoS) concept can replace the current System-in-Package (SiP) approach for mm-wave systems.

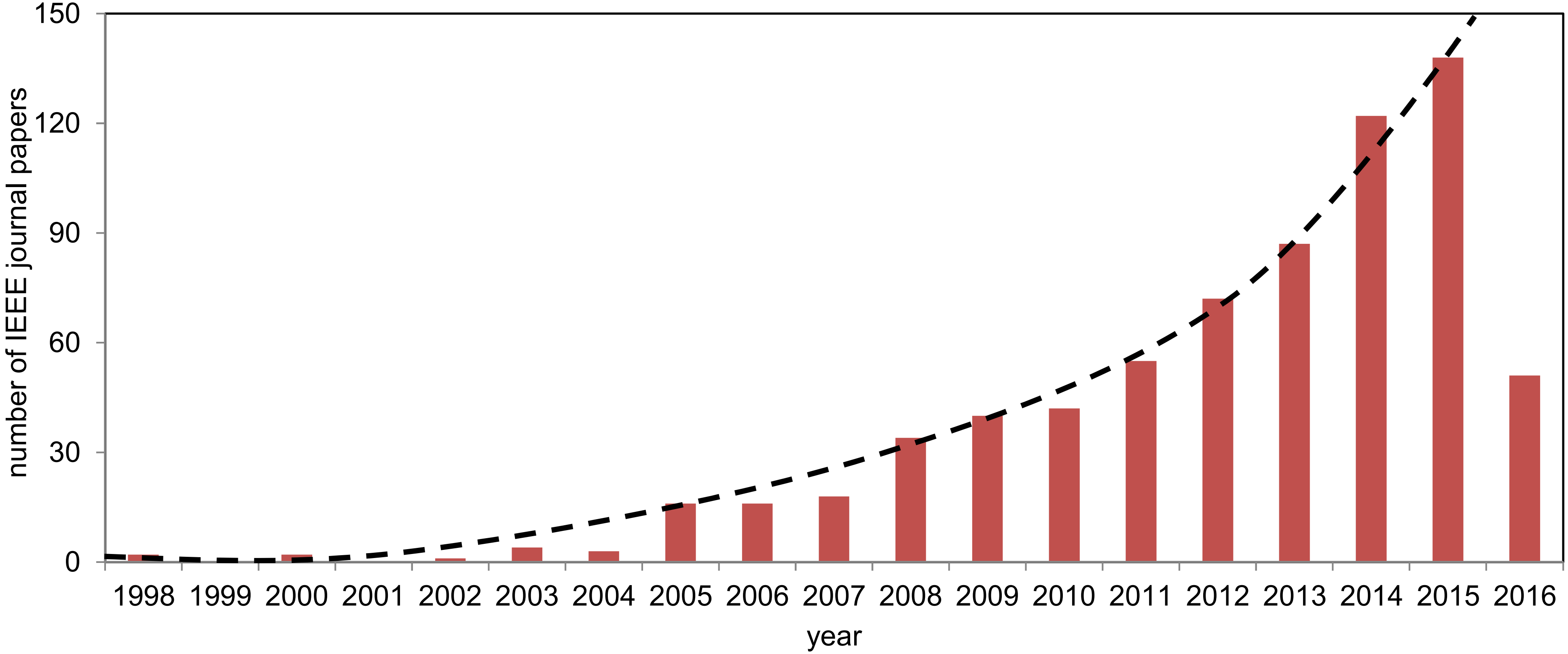
SYSTEMS-ON-SUBSTRATE (SOS)



Z. Li and K. Wu, “24-GHz Frequency-Modulation Continuous-Wave Radar Front-End System-on-Substrate,” *IEEE Trans. on Microwave Theory and Techniques*, Vol. 56, No. 2, pp. 278-285, Feb. 2008.

Evolution of Research on SIW

In ten years, SIW technology has reach incredible popularity!



Source: http://ieeexplore.ieee.org/ - Updated March 30, 2016

Part 3 – New Materials:

Paper, Textile, 3D-Printing

Paper-based

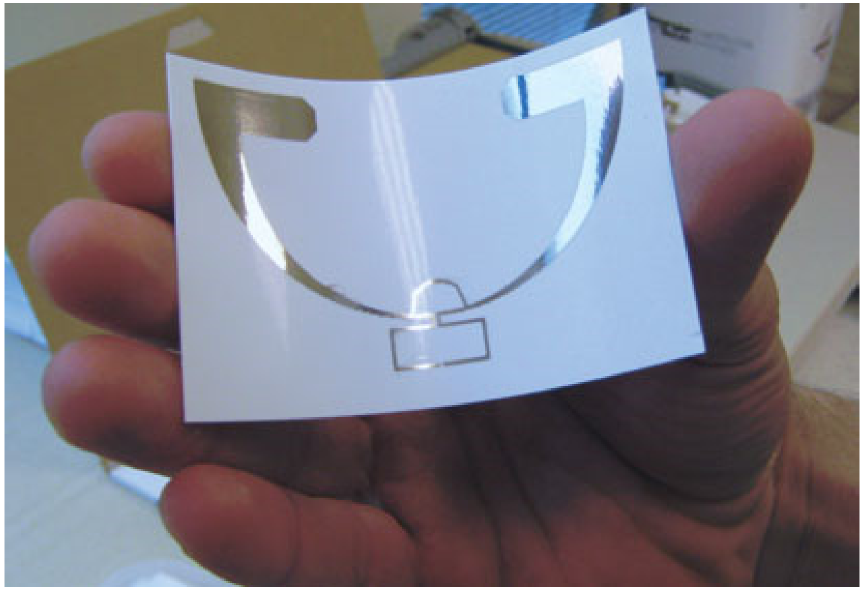
Substrate Integrated Waveguide

PAPER-BASED CIRCUITS

The use of **paper** have been recently proposed for the development of circuits and antennas.

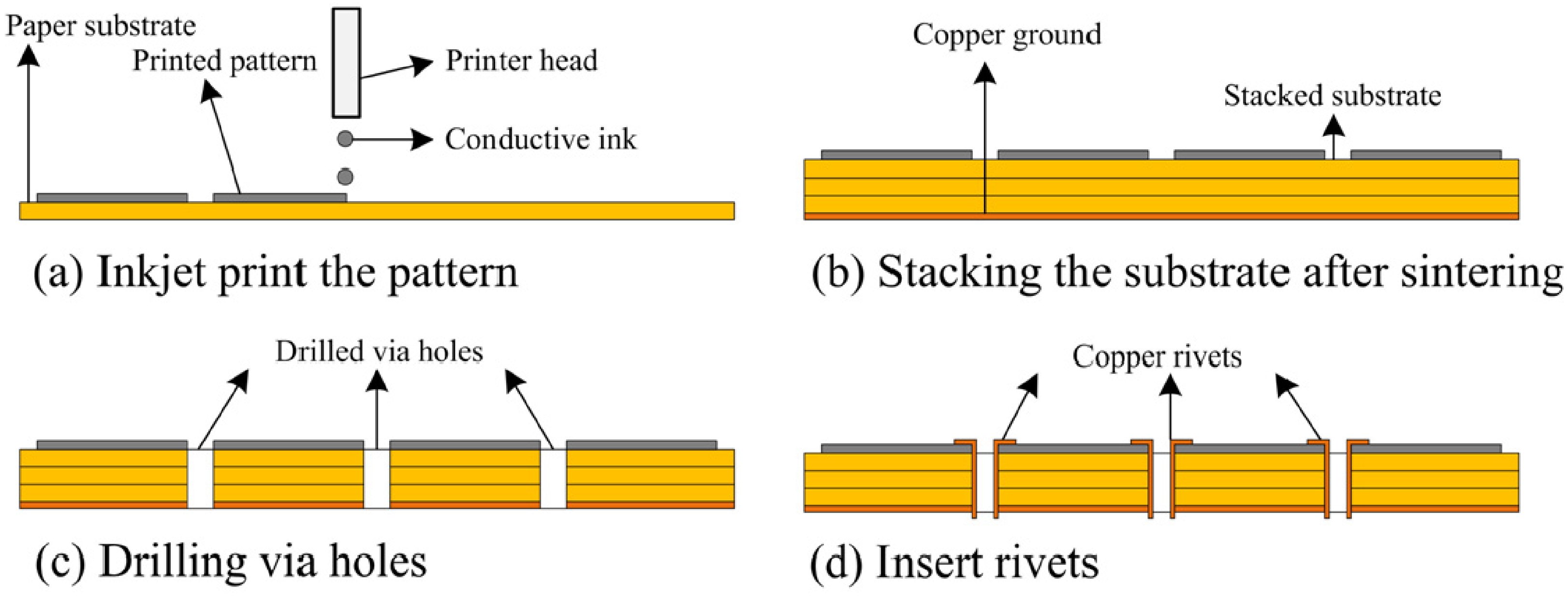
Advantages: eco-friendly, low cost and flexible

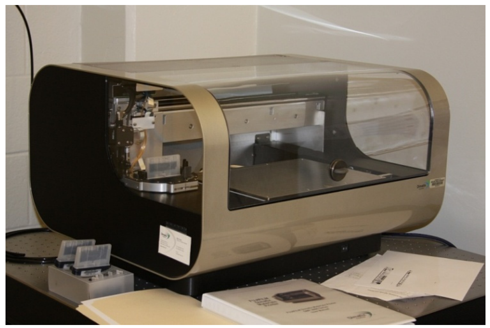
Disadvantages: losses



INK-JET PRINTING FABRICATION

The fabrication process of SIW structures on paper is based on ink-jet printing of the metalized layers and rivets to implement the vias.

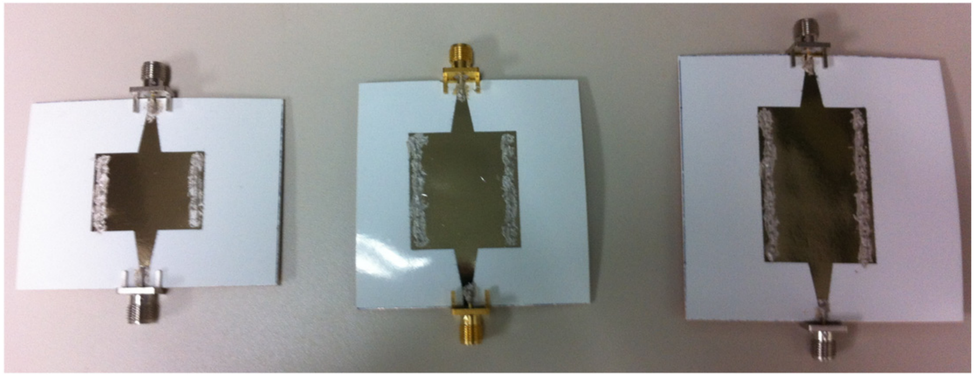


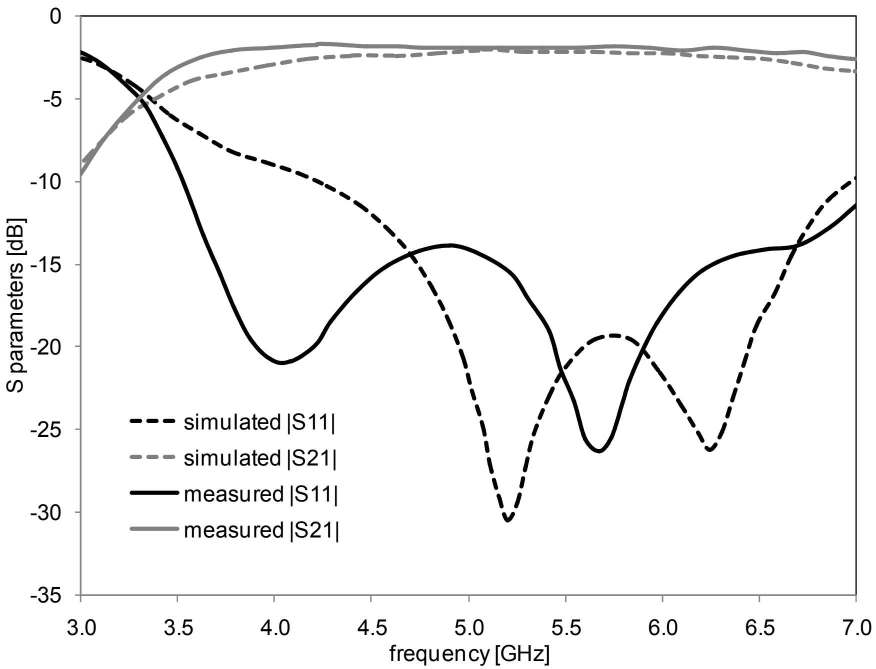


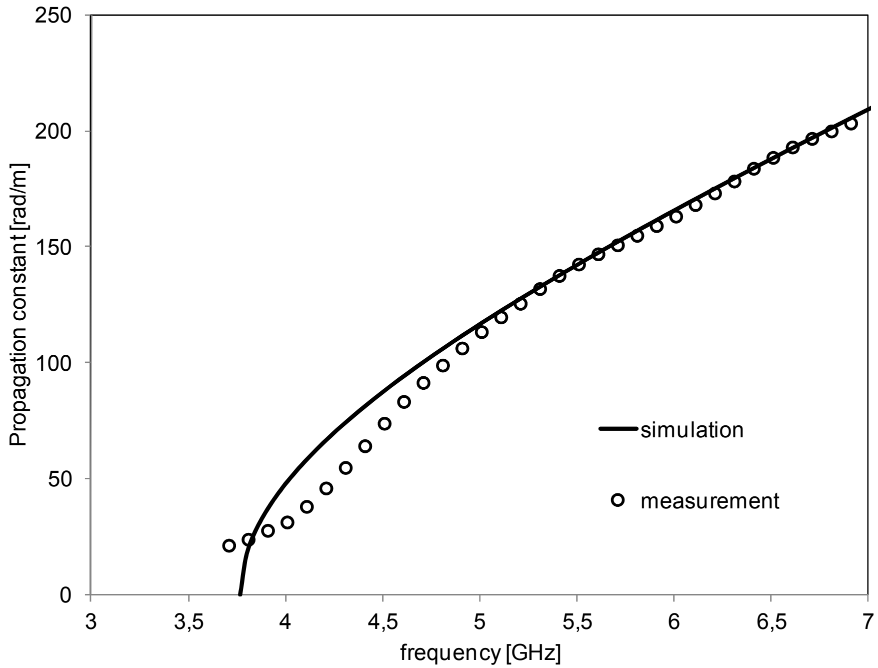
Collaboration between University of Pavia & GATech, Atlanta

SIW Interconnect on Paper

SIW interconnects with different length have been designed and manufactured.

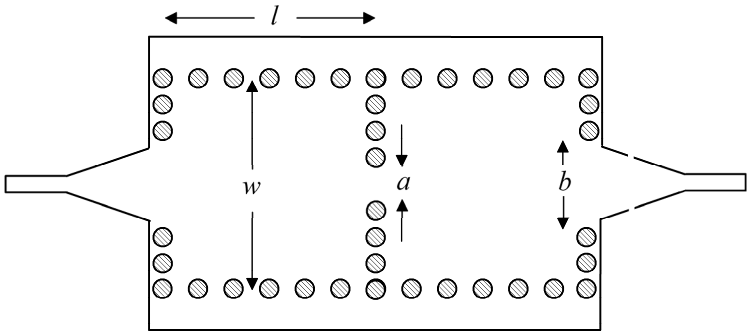


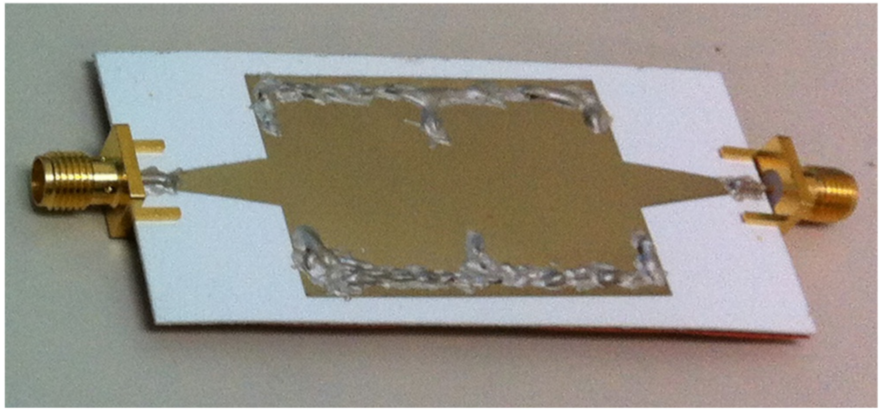


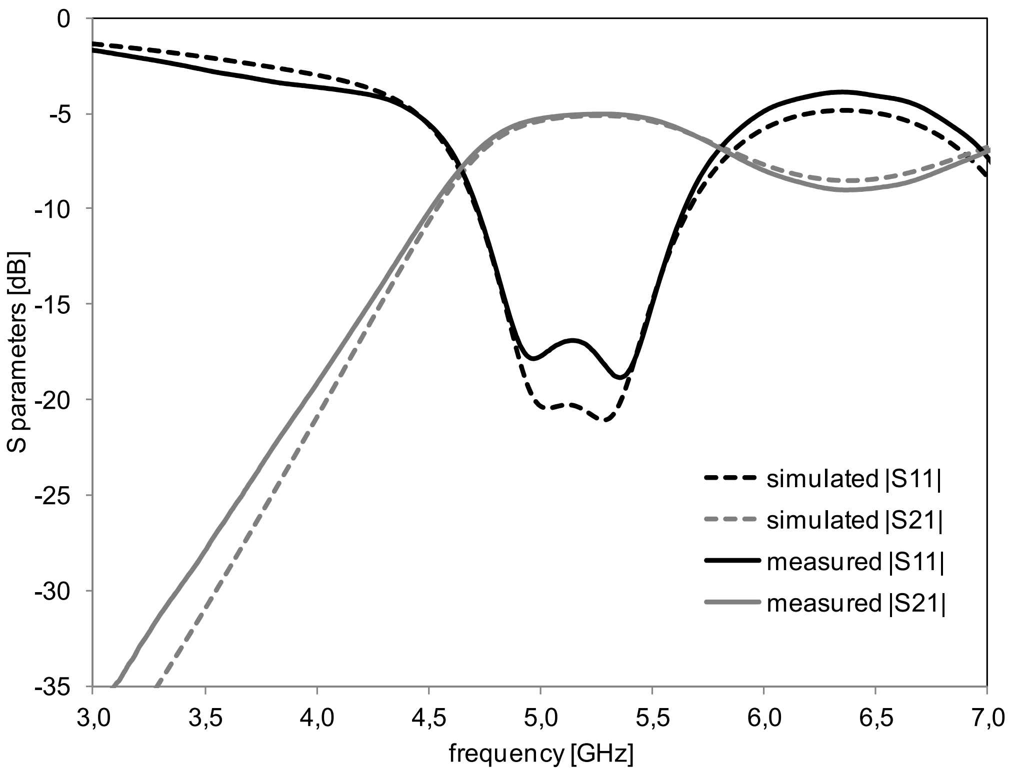


insertion loss 0.85 dB/cm at 5 GHz

SIW FILTER ON PAPER



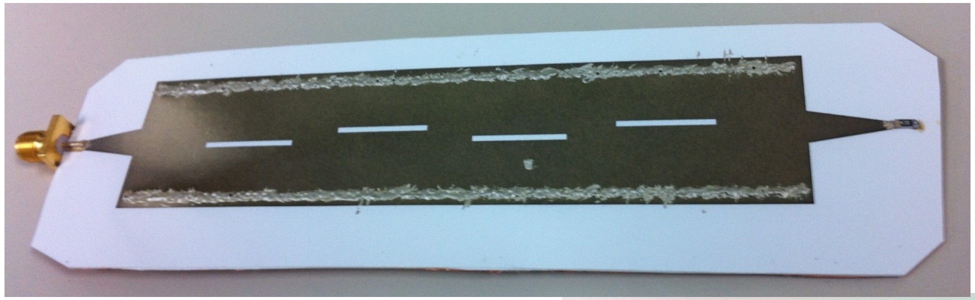




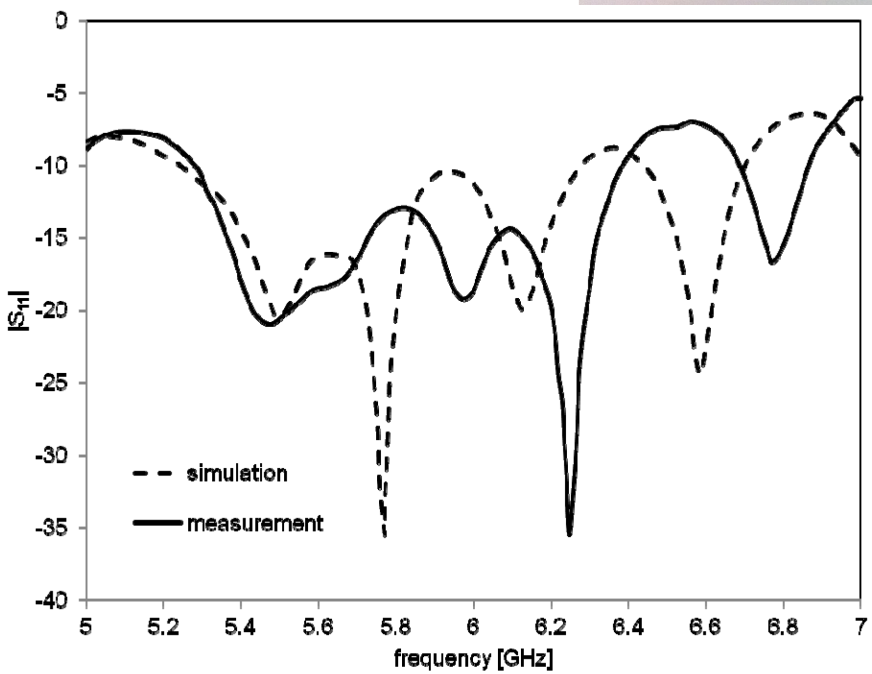
S. Kim, B. Cook, T. Le, J. Cooper, H. Lee, V. Lakafosis, R. Vyas, R. Moro, M. Bozzi, A. Georgiadis, A. Collado, and M. Tentzeris, "Inkjet-printed Antennas, Sensors and Circuits on Paper Substrate," IET Microwaves, Antennas and Propagation, Vol. 7, No. 10, pp. 858–868, July 16, 2013.

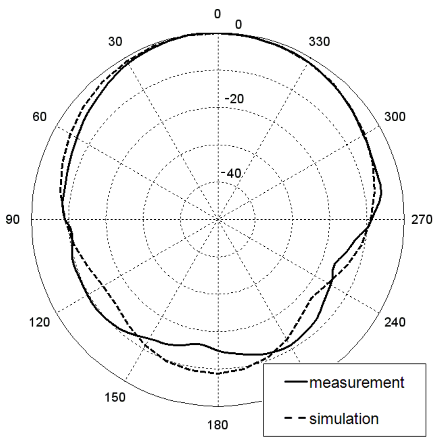
(2015 Premium Award for Best Paper in IET Microwave Antennas & Propagation)

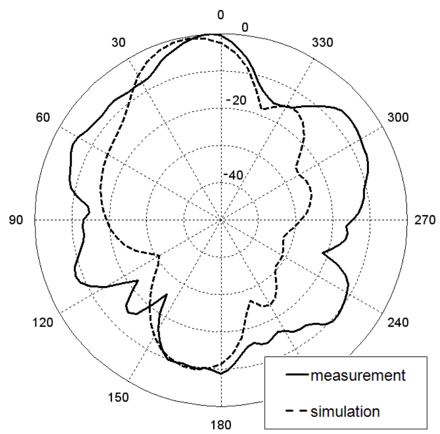
SIW ANTENNA ON PAPER



R. Moro, S. Kim, M. Bozzi, M. Tentzeris, "Inkjet-Printed Paper-Based Substrate Integrated Waveguide (SIW) Components and Antennas," *International Journal of Microwave and Wireless Technologies*, 2013.

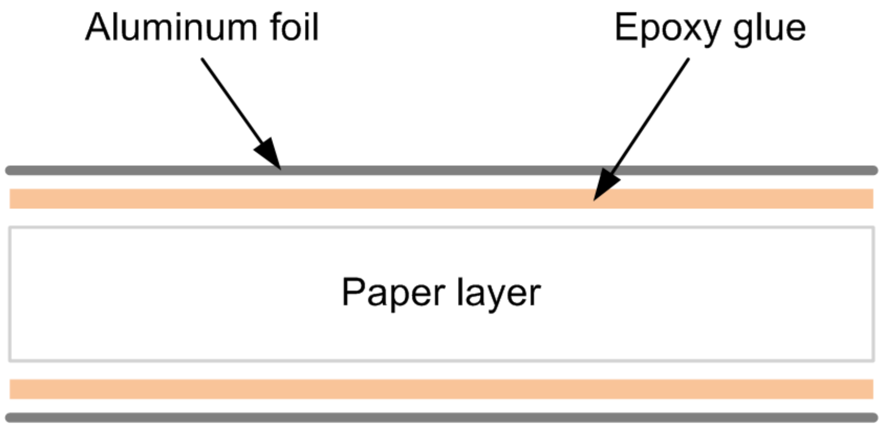


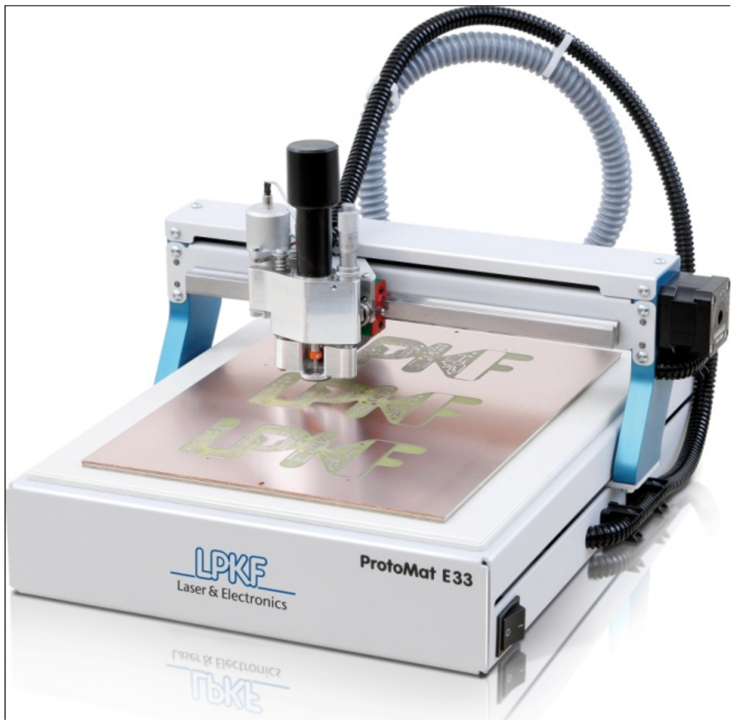




Fabrication by Milling

The paper layers are stacked with stick-glue. Two **aluminum foils** are pasted at top and bottom with epoxy-glue.





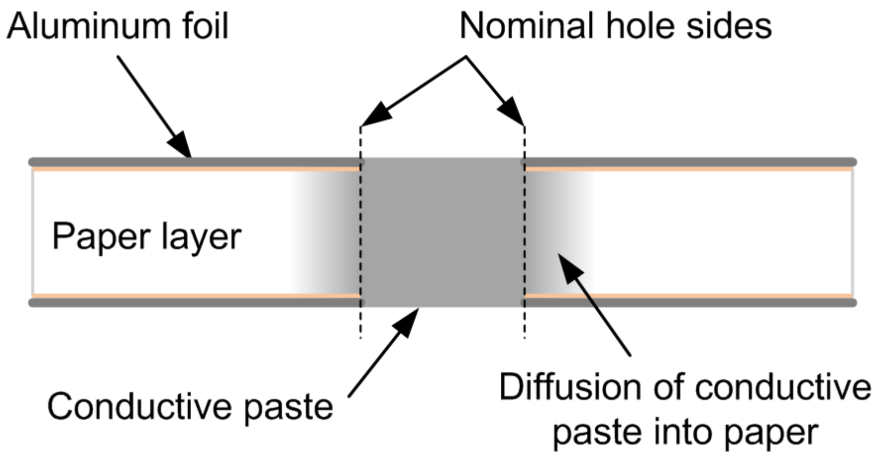
A CNC **milling machine** is used to pattern the conductive surface and to drill the holes in the paper.

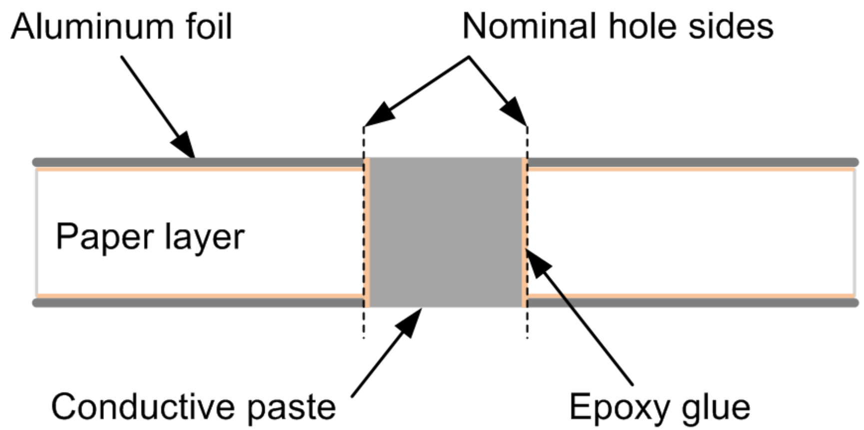
FABRICATION BY MILLING

The via holes are metalized using **conductive paste**.

A **thin film** of epoxy glue is used to avoid its diffusion in the substrate.

Heating processes are required.



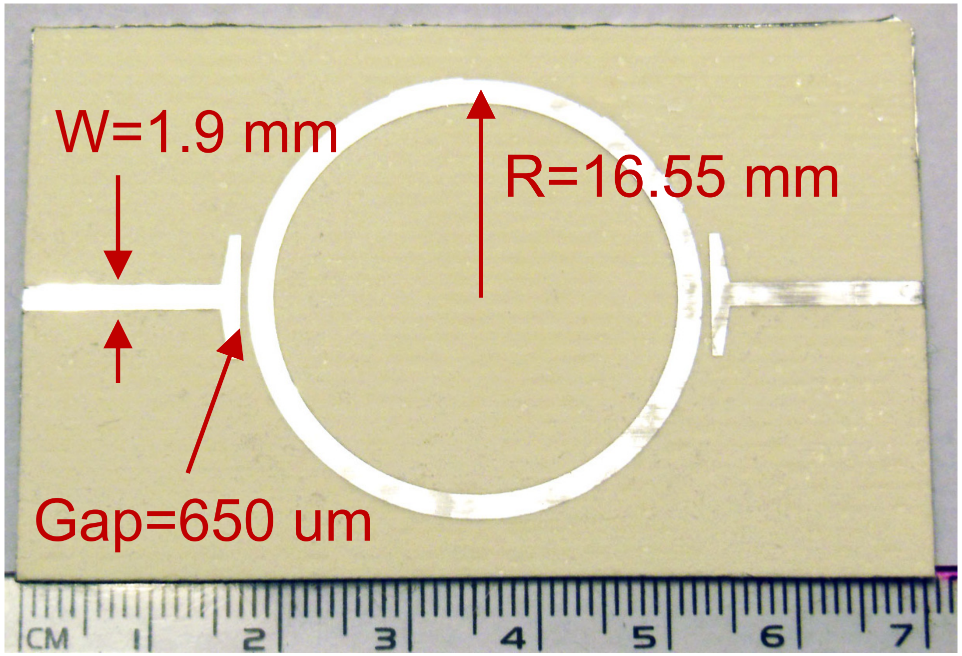


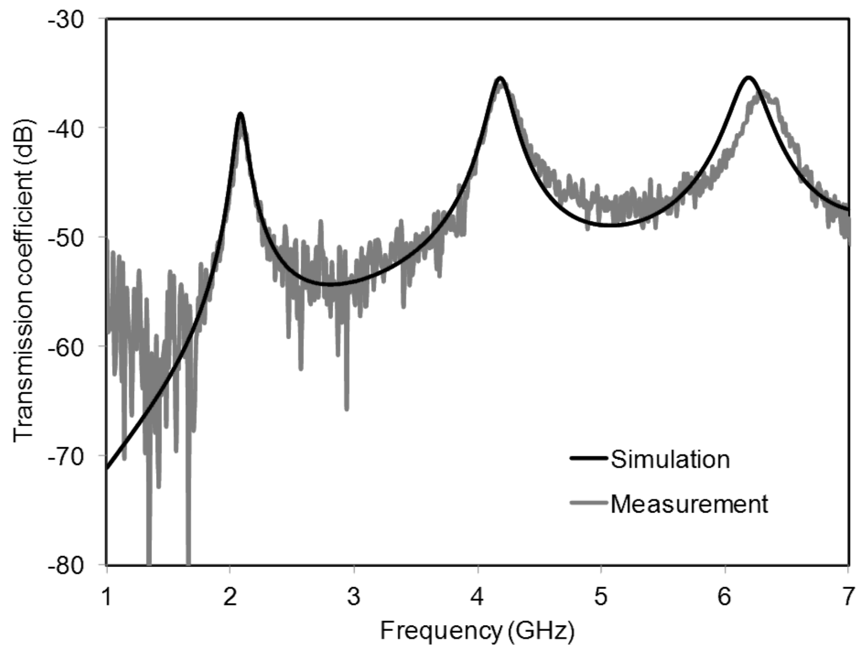
S. Moscato, R. Moro, M. Pasian, M. Bozzi, and L. Perregrini, "An Innovative Manufacturing Approach for Paper-based Substrate Integrated Waveguide Components and Antennas," *IET Microwaves, Antennas and Propagation* (in print).

PAPER CHARACTERIZATION

The dielectric characteristics of the paper substrates have been measured by using a ring resonator.

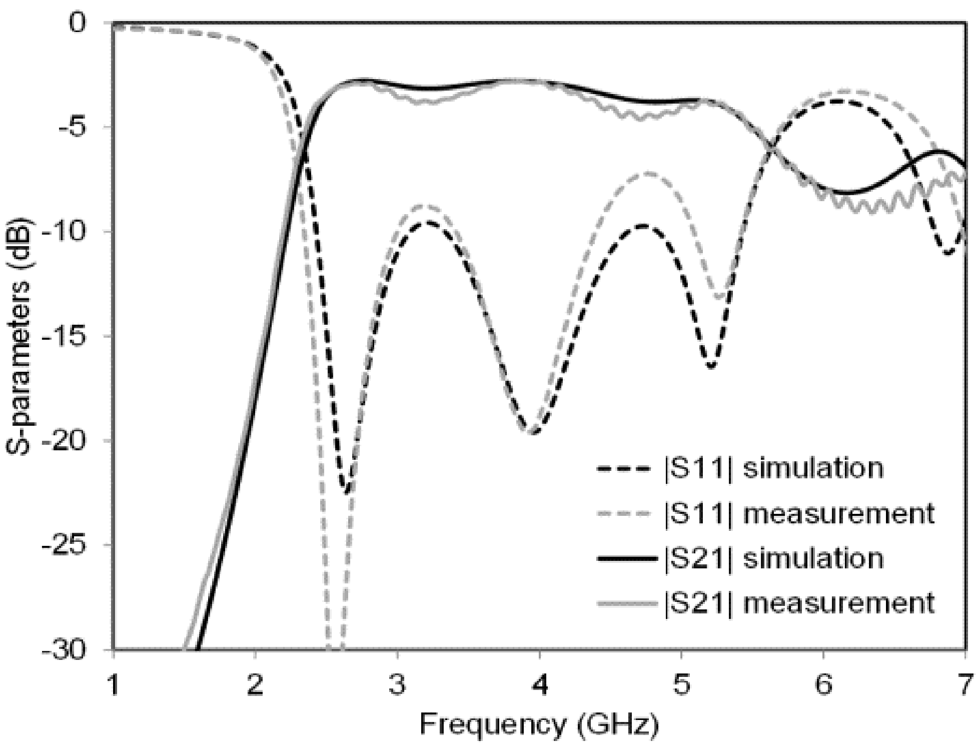
The resulting characteristics are ε_r=2.2 and tanδ=0.04.

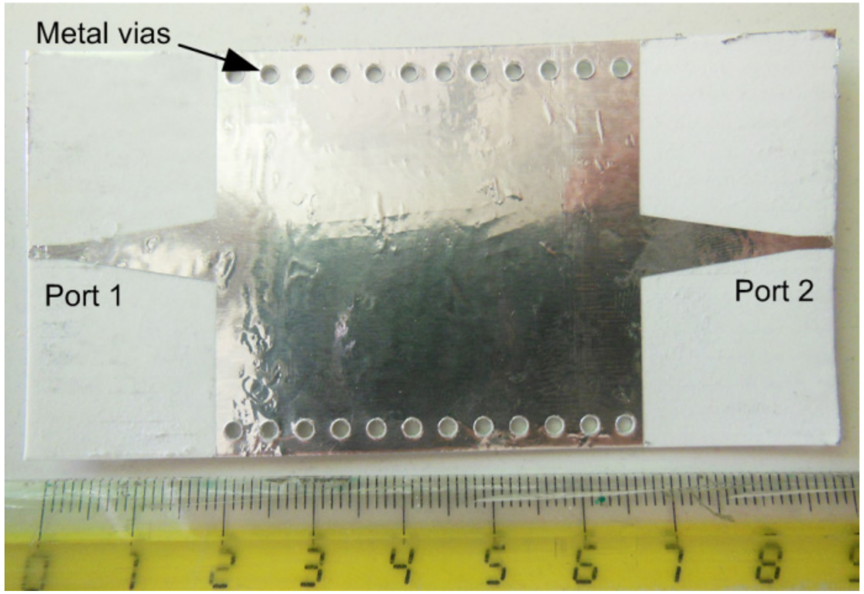




SIW INTERCONNECTS ON PAPER

A straight SIW interconnect with cutoff frequency at 2.5 GHz was fabricated on paper substrate.

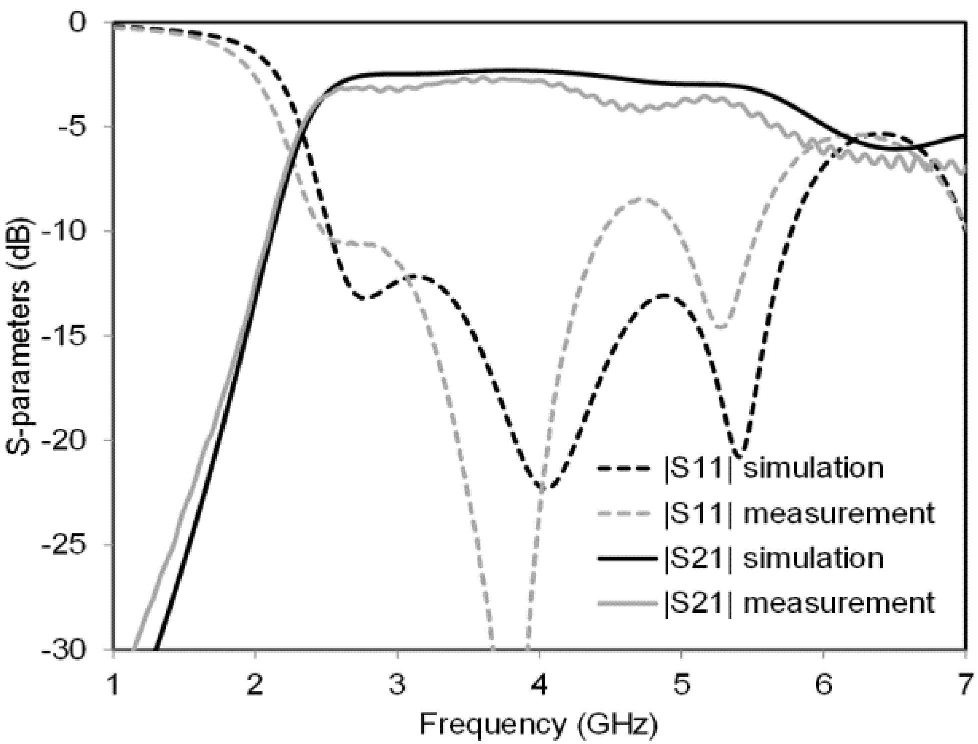


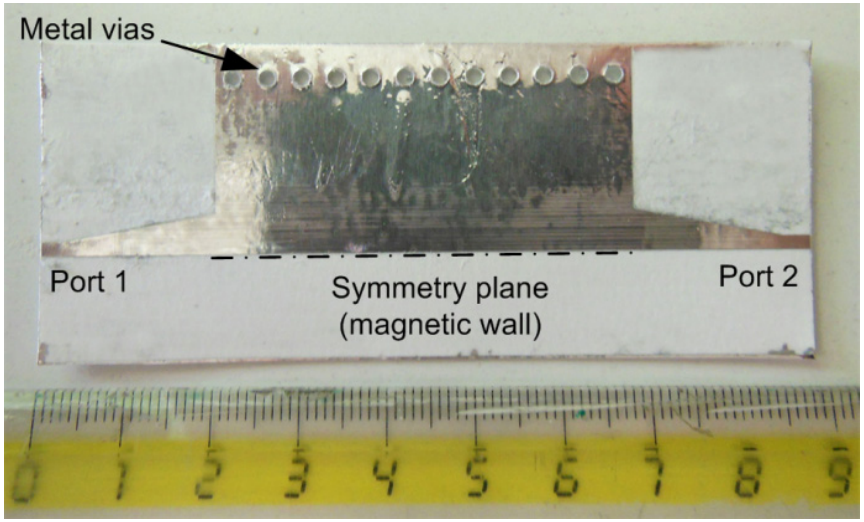


attenuation constant 0.3 dB/cm at 4 GHz

SIW Interconnects on Paper

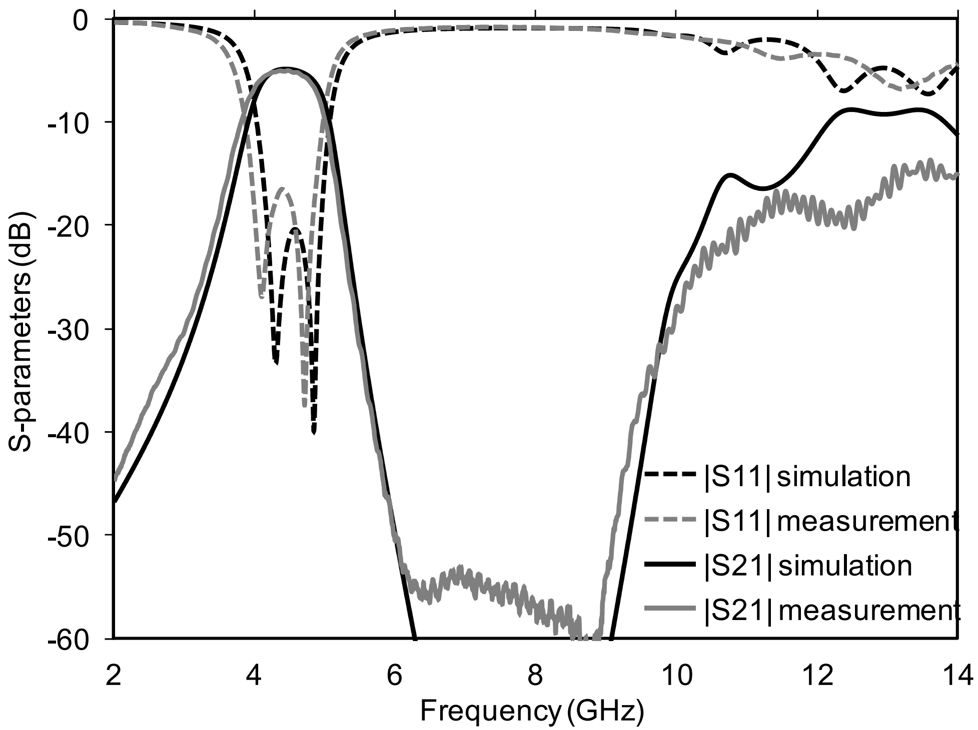
The use of half-mode SIW allows reducing the width of the structure of 50%, without affecting the performance.

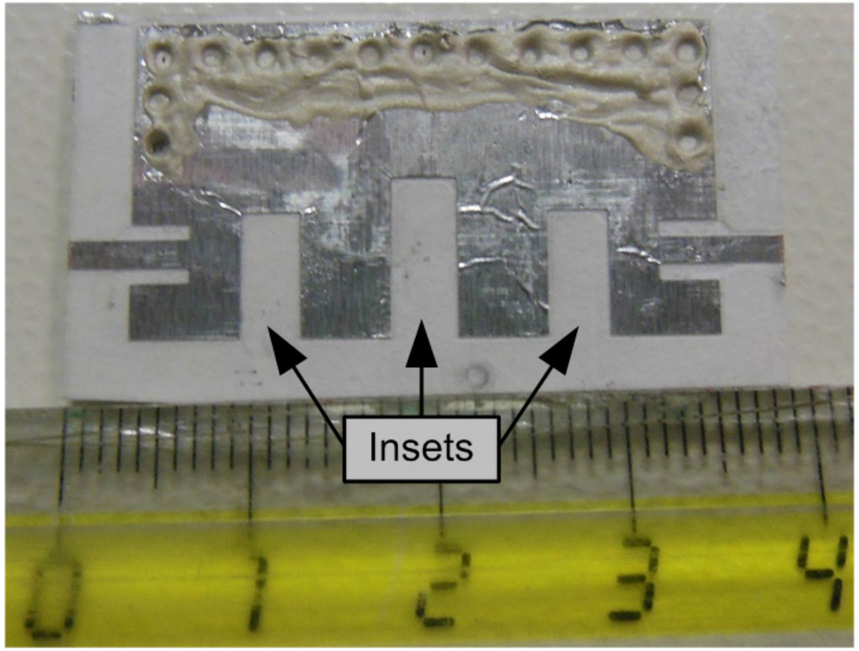




SIW Filters on Paper

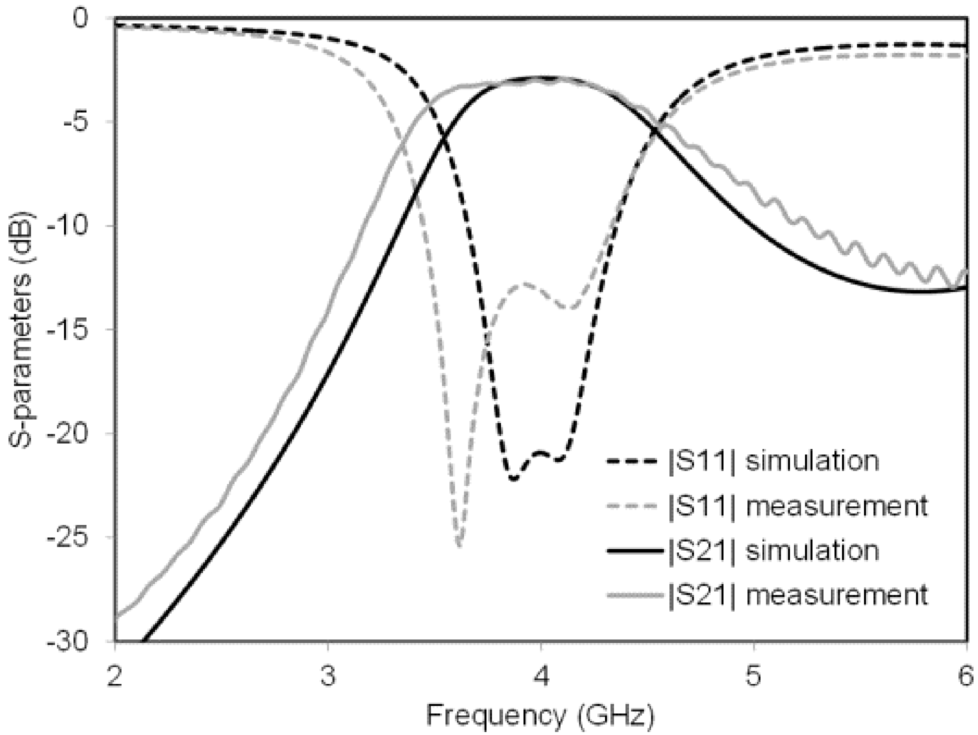
Half-mode SIW filter with pass-band is centered at 4.5 GHz and wide out-of-band region. The footprint reduction is close to 75% with respect to an iris filter.

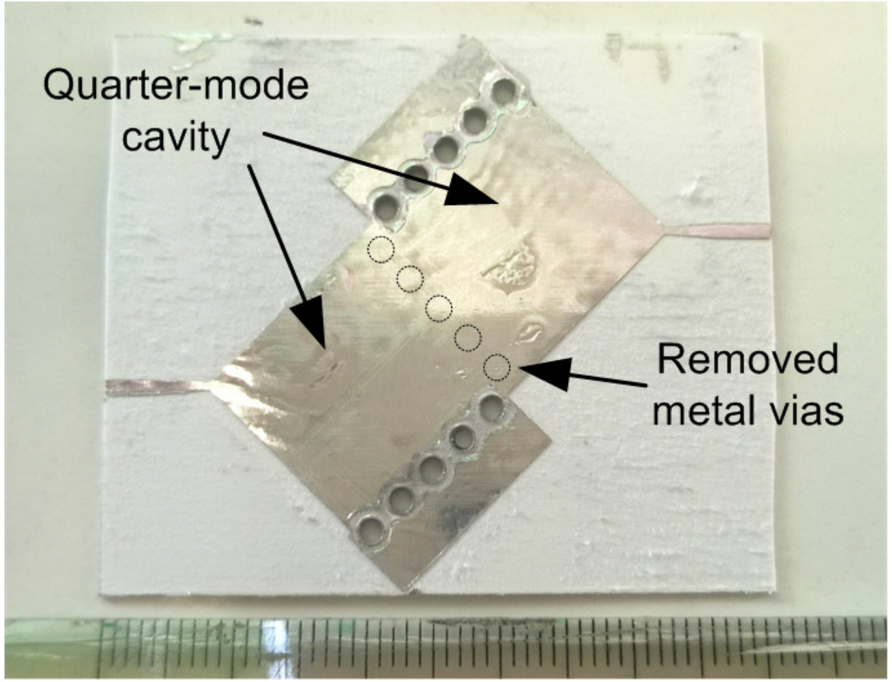




SIW FILTERS ON PAPER

Quarter-mode SIW filter: each quarter mode resonator has a footprint reduced by 75% with respect of the full one.



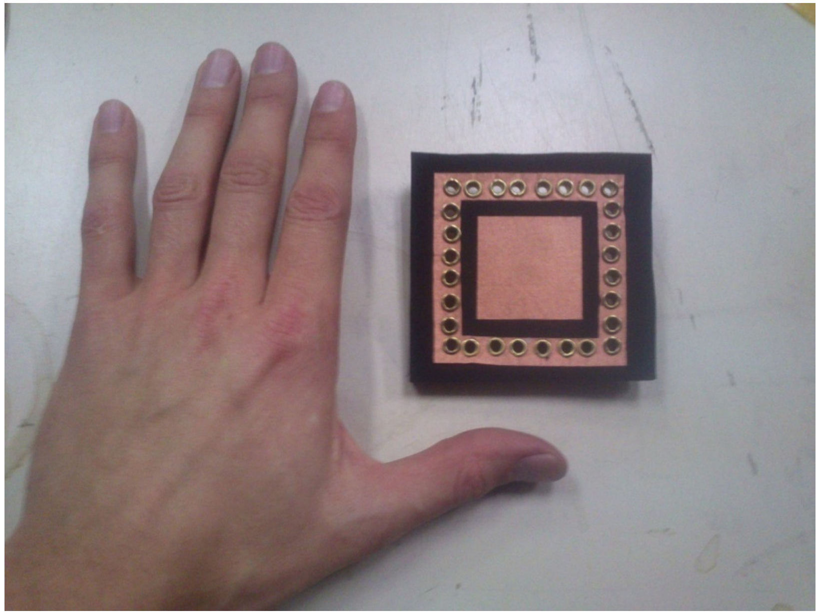


Wearable SIW Structures on Textile

Circuits on Textile

Circuits and antennas on textile have been recently proposed for implementing wearable devices.

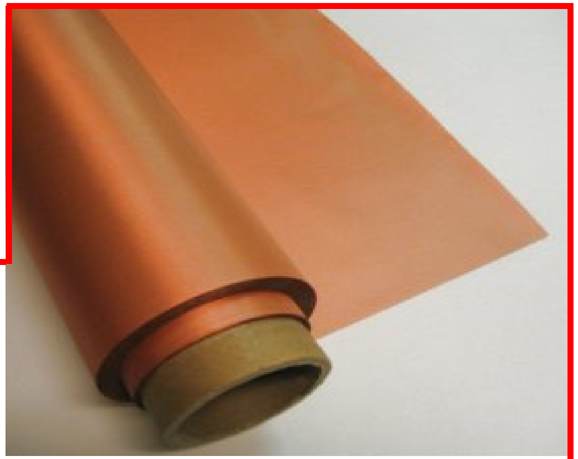
Applications: localization of firefighters inside buildings, biomedical use.



Collaboration between University of Pavia & Ghent University, Belgium

FABRICATION OF TEXTILE SIW

The substrate is closed cell expanded rubber with a thickness of 3.94 mm.



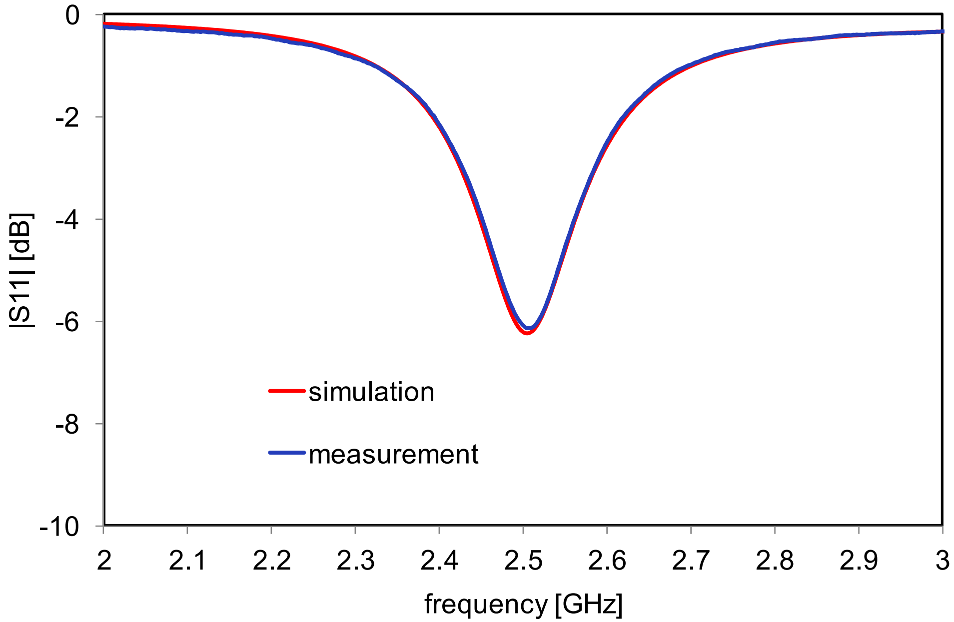
The metal layers are an electrotextile called Flectron®.

Its surface resistivity is R_s = 0.18 Ω/sq

Rivets are used for the metallization of via holes

R. Moro, S. Agneessens, H. Rogier, A. Dierck, and M. Bozzi, "Textile Microwave Components in Substrate Integrated Waveguide Technology," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 63, No. 2, pp. 422-432, February 2015..

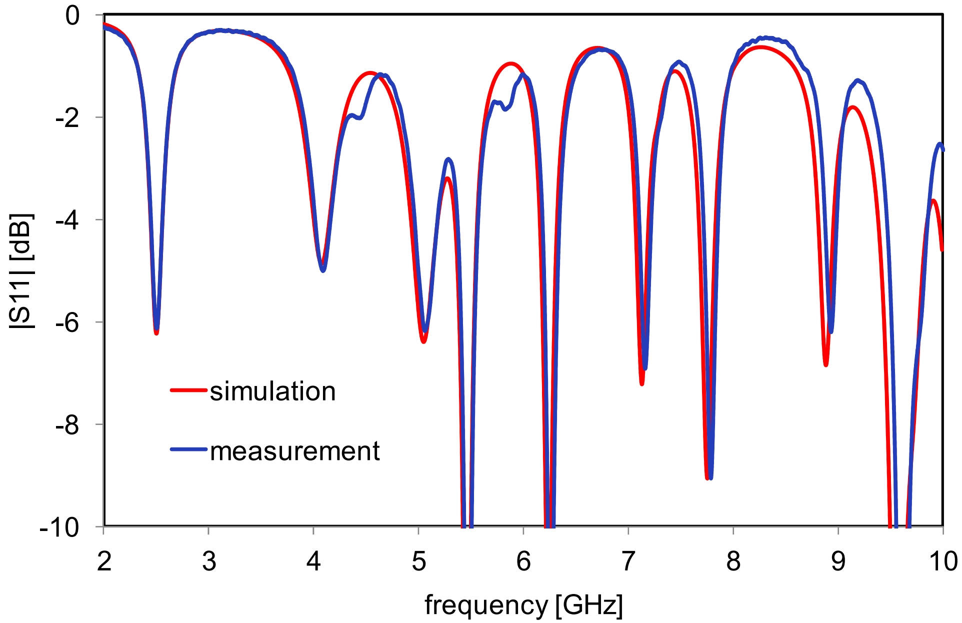
TEXTILE SIW CAVITY



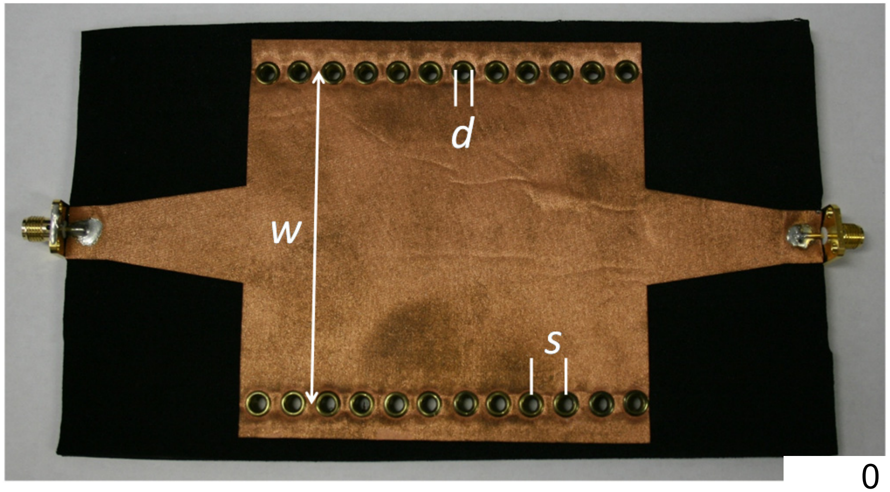
Foam characteristics at 2.45 GHz

dielectric permittivity $\varepsilon_r = 1.45$

loss angle $\tan\delta = 0.017$



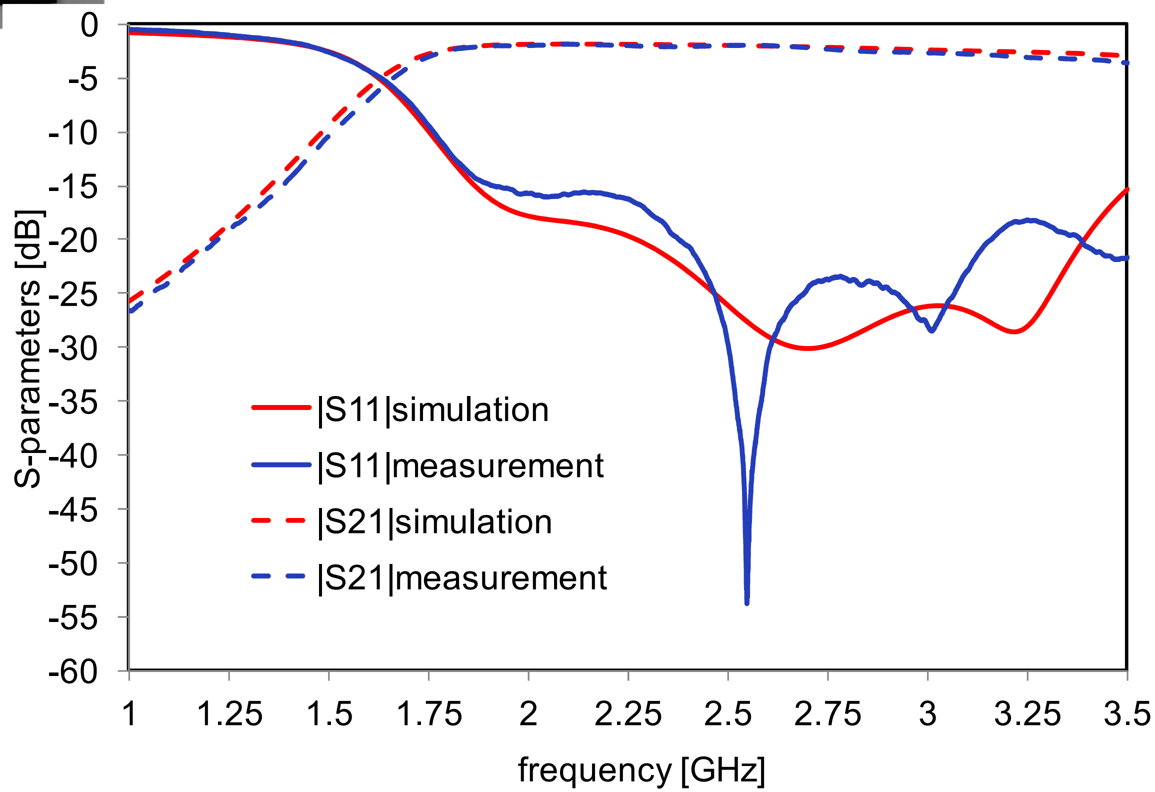
TEXTILE SIW INTERCONNECT



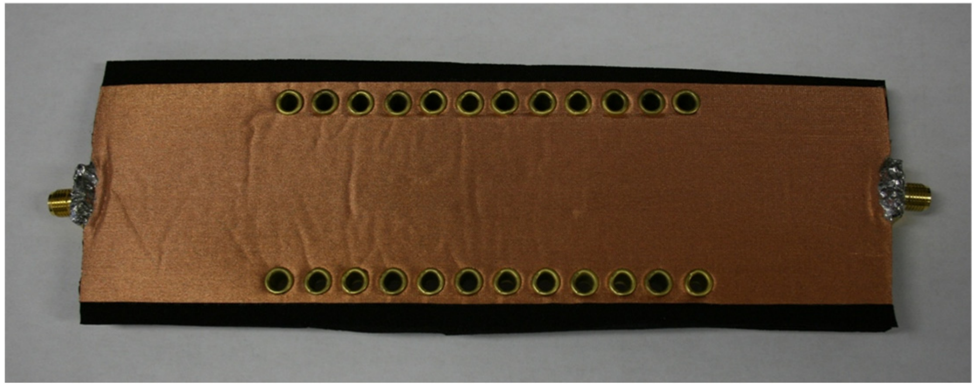
Textile SIW transmission line operating at 2.45 GHz: *w* = 79 mm, *s* = 8mm, *d* = 4 mm.

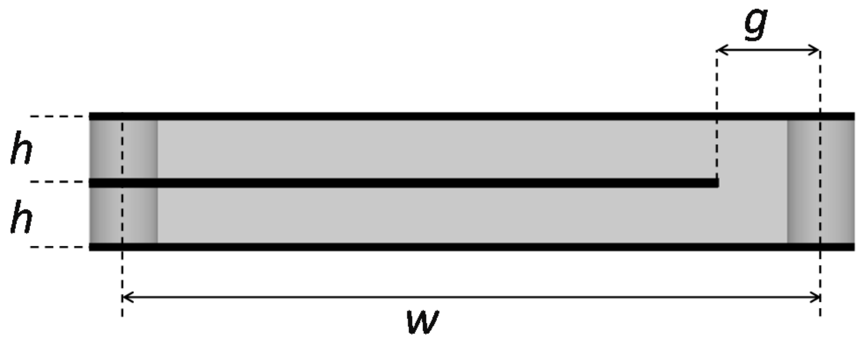
The cut-off frequency is 1.62 GHz.

The measured insertion loss at 2.45 GHz is 2 dB.



FOLDED SIW INTERCONNECT

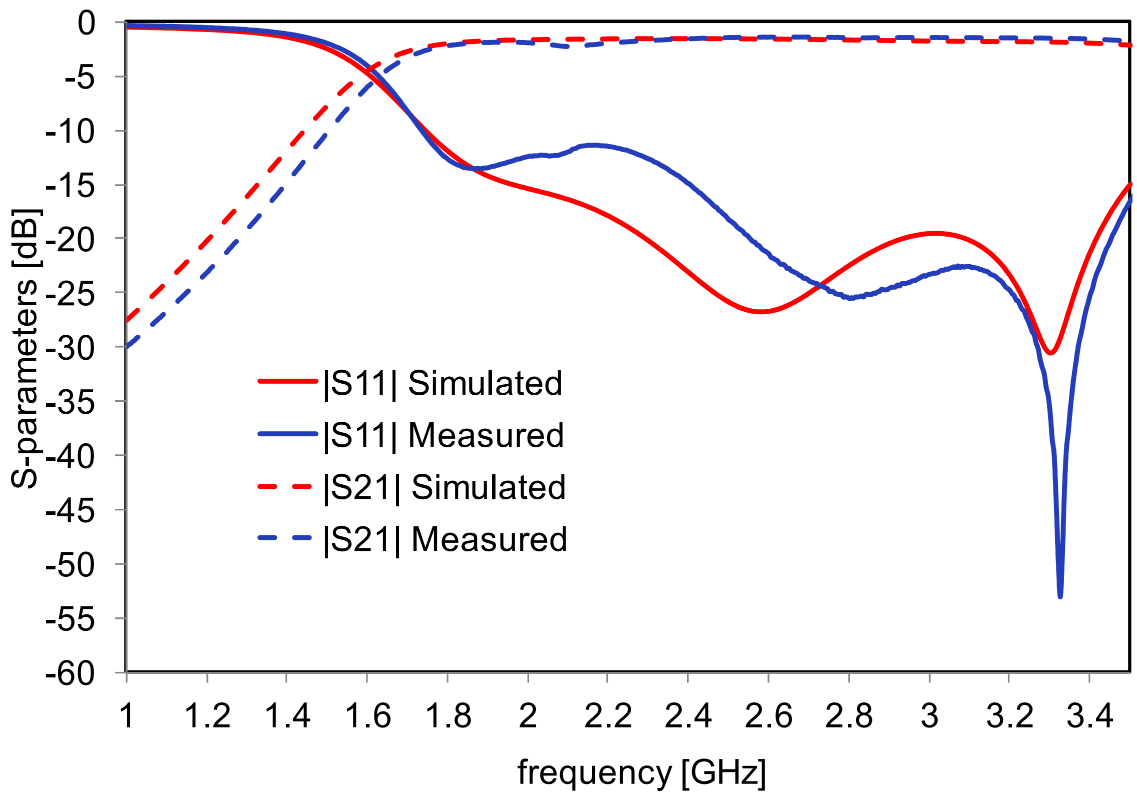




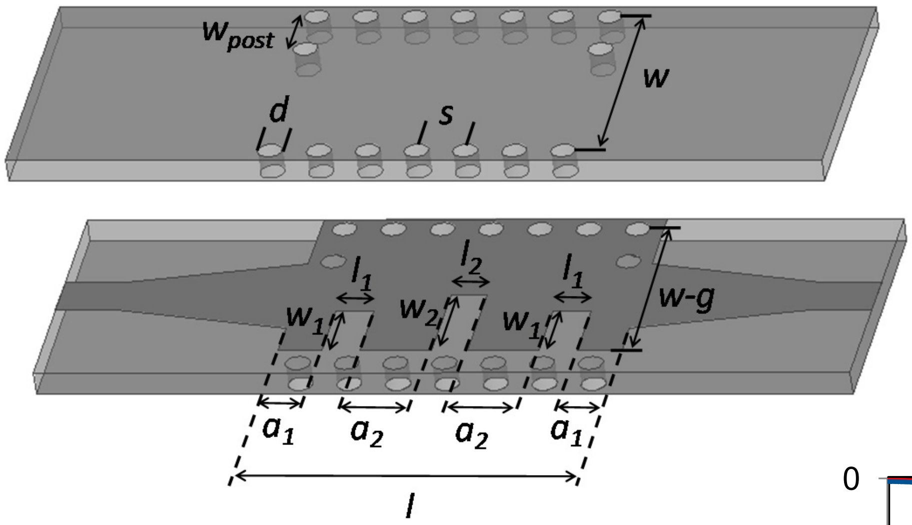
gap width g = 4 mm

SIW width w = 41.2 mm

(48% reduction)

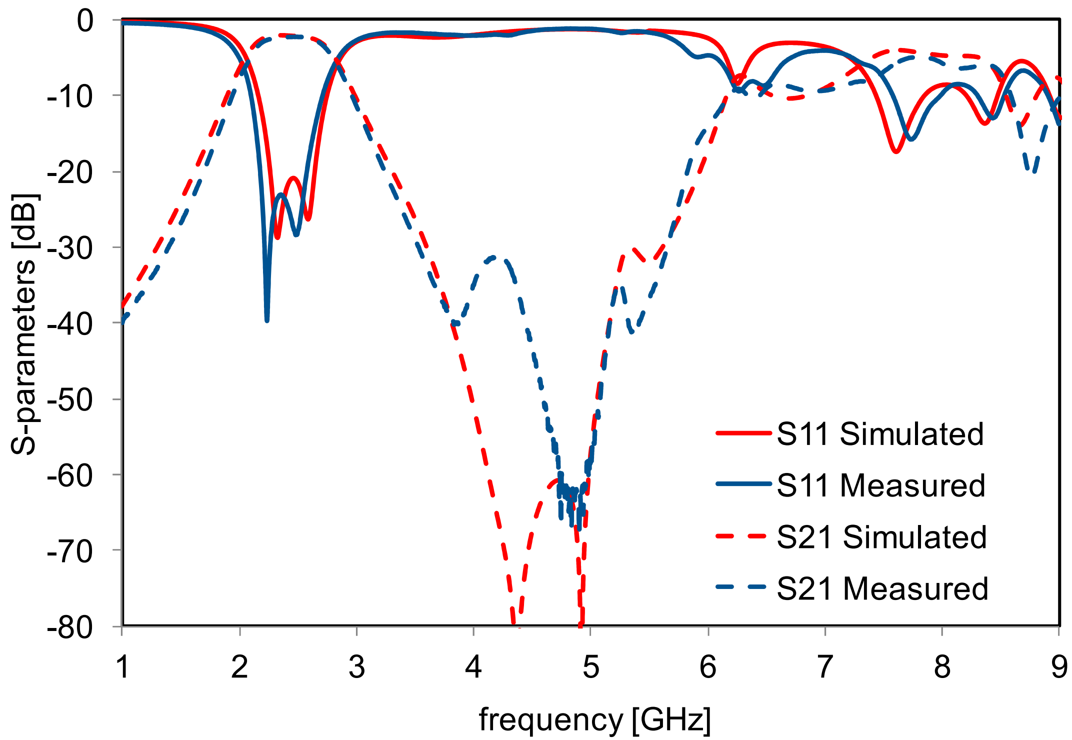


FOLDED SIW FILTER



Band pass filter operating in the 2.45 GHz ISM band

Wide out of band bandwidth

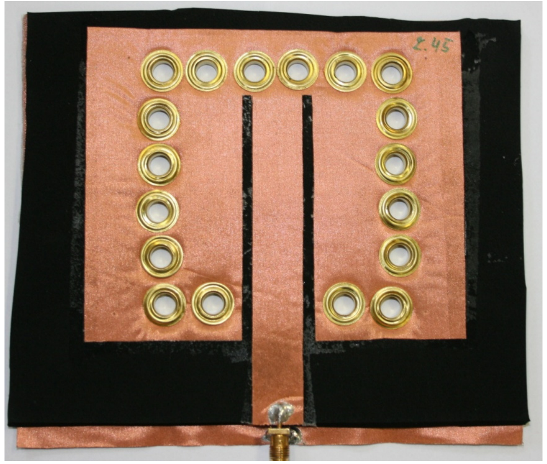


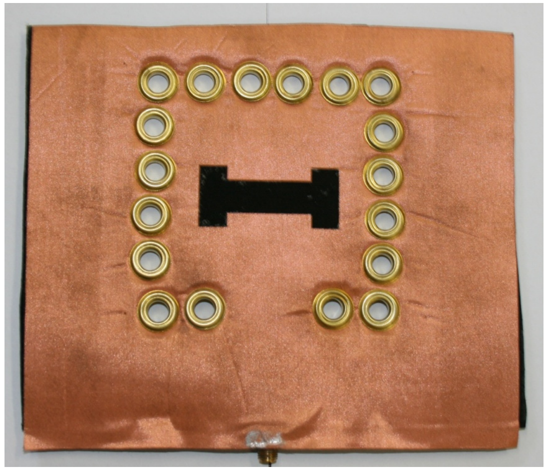
TEXTILE SIW ANTENNA

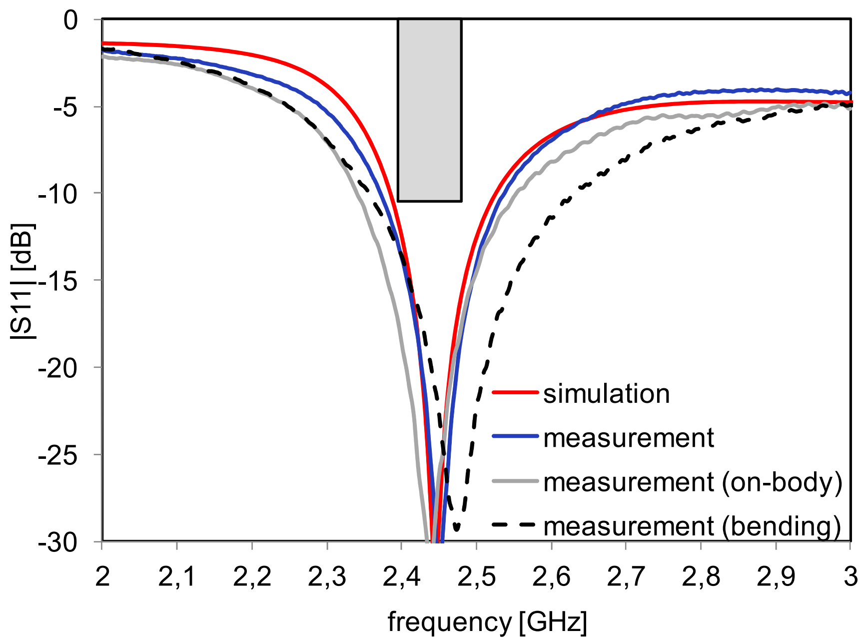
Cavity-backed SIW antenna operating at 2.45 GHz

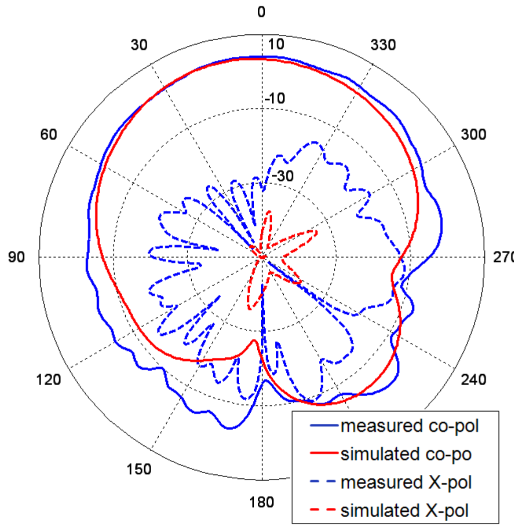
R. Moro, S. Agneessens, H. Rogier, M. Bozzi, "Wearable Textile Antenna in Substrate Integrated Waveguide Technology," *Electronics Letters,* 2012

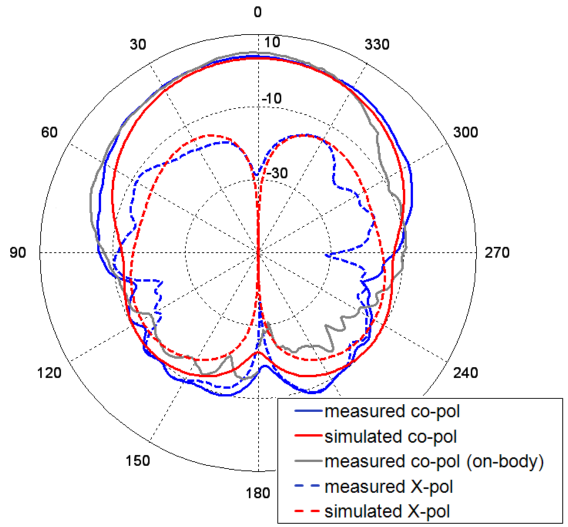
(2014 Premium Award for Best Paper in Electronics Letters)



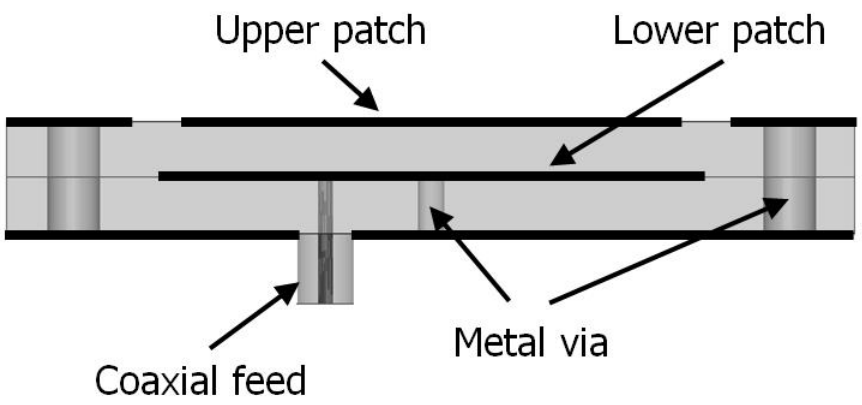


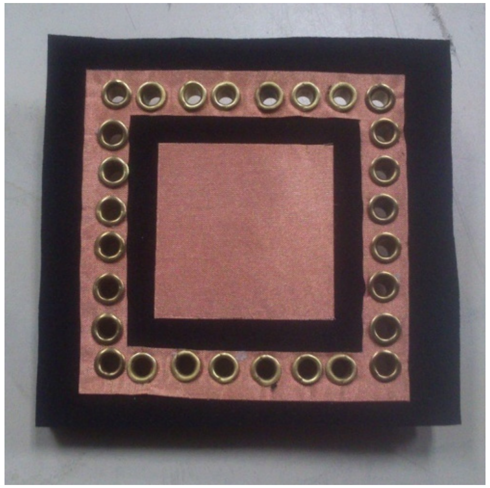




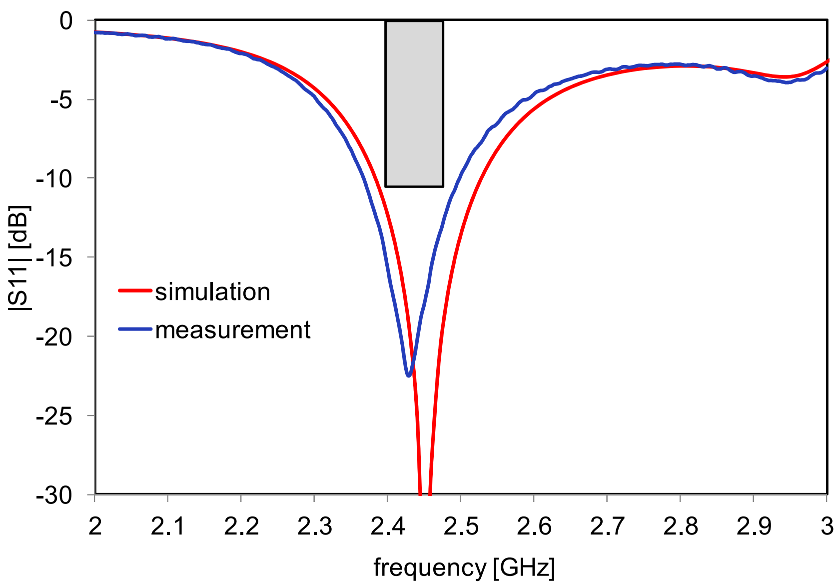


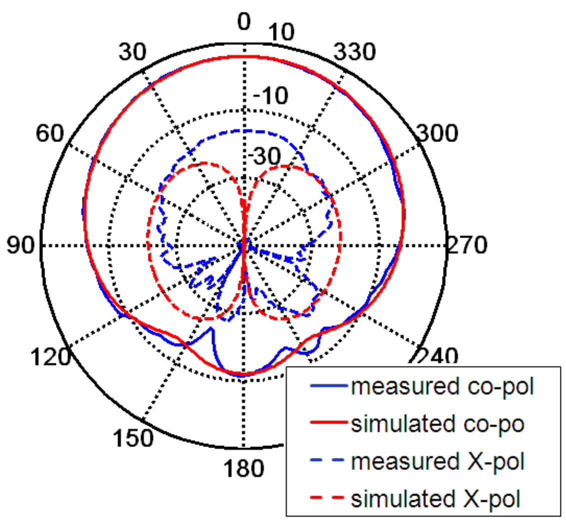
TEXTILE FOLDED SIW ANTENNA

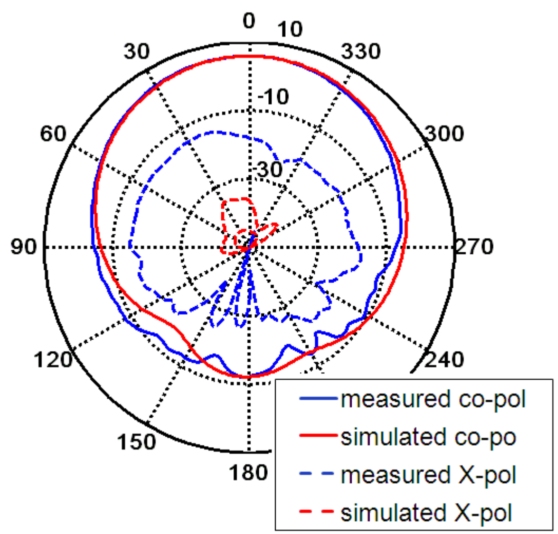




size reduction of 43%





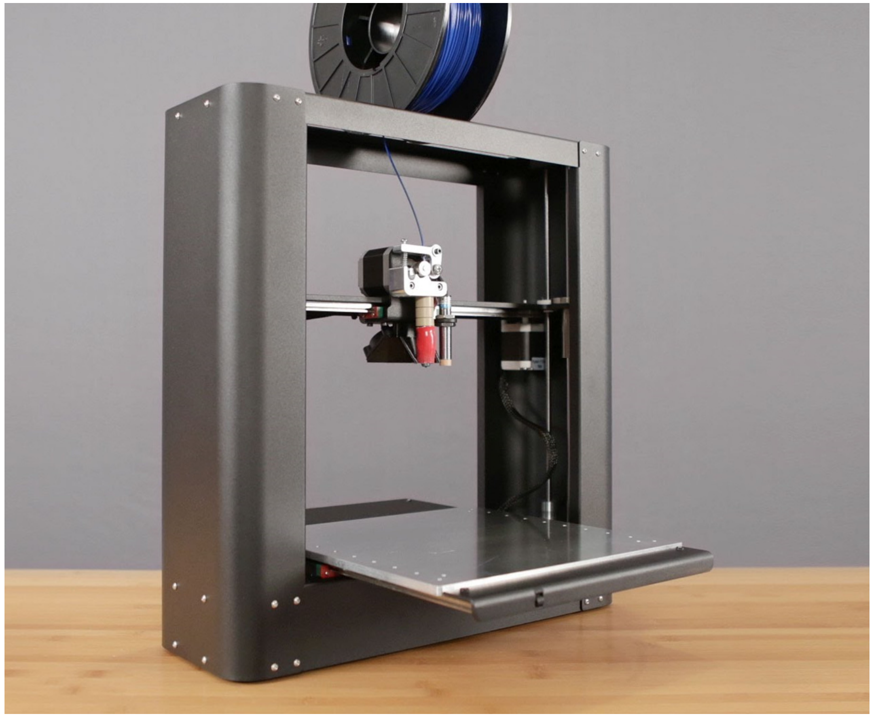


3D-Printing of Microwave Components

ADDITIVE MANUFACTURING

Additive manufacturing represents an emerging enabling technology for a wide range of electronic devices:

- fast prototyping;
- reasonable accuracy;
- low fabrication cost;
- fully 3D topologies.

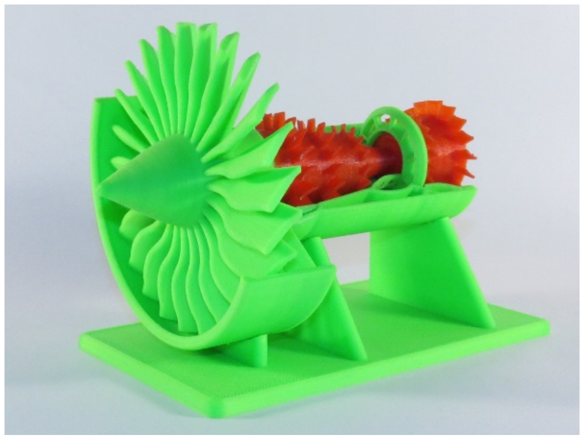


Printerbot Metal Plus – 1000$

Collaboration University of Pavia & GATech, Atlanta, USA

FUSED DEPOSITION MODELING (FDM)

FDM is an **extrusion-based 3D-printing technique**. a plastic filament is heated and extruded from a nozzle, which lays down the material to form 2D layers. The overlap of 2D layers results into the 3D printed structure.

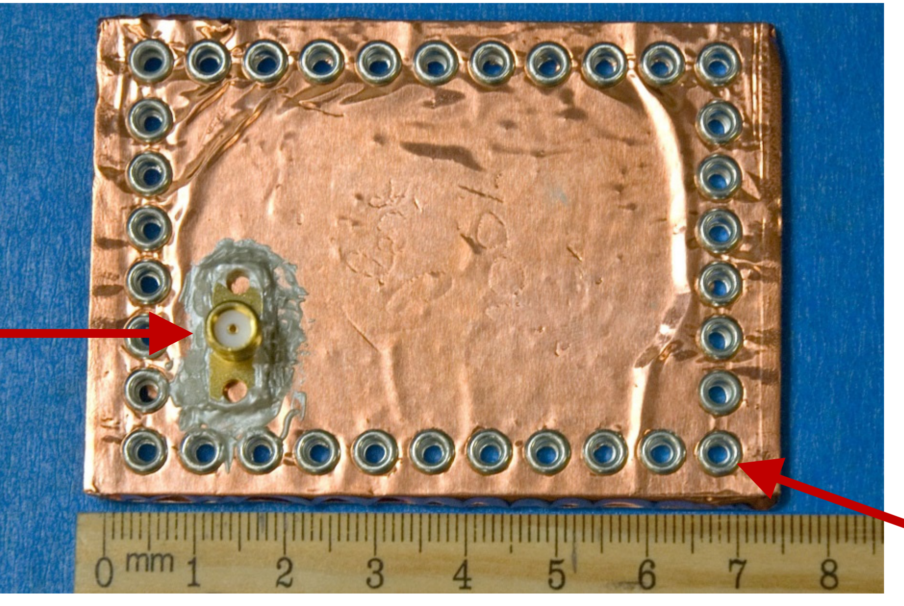


3D-Printed SIW Cavity

The characterization technique concerns the manufacturing of a rectangular SIW cavity and a numerical fitting of the scattering parameters.

67.2 mm

Coaxial feeding point



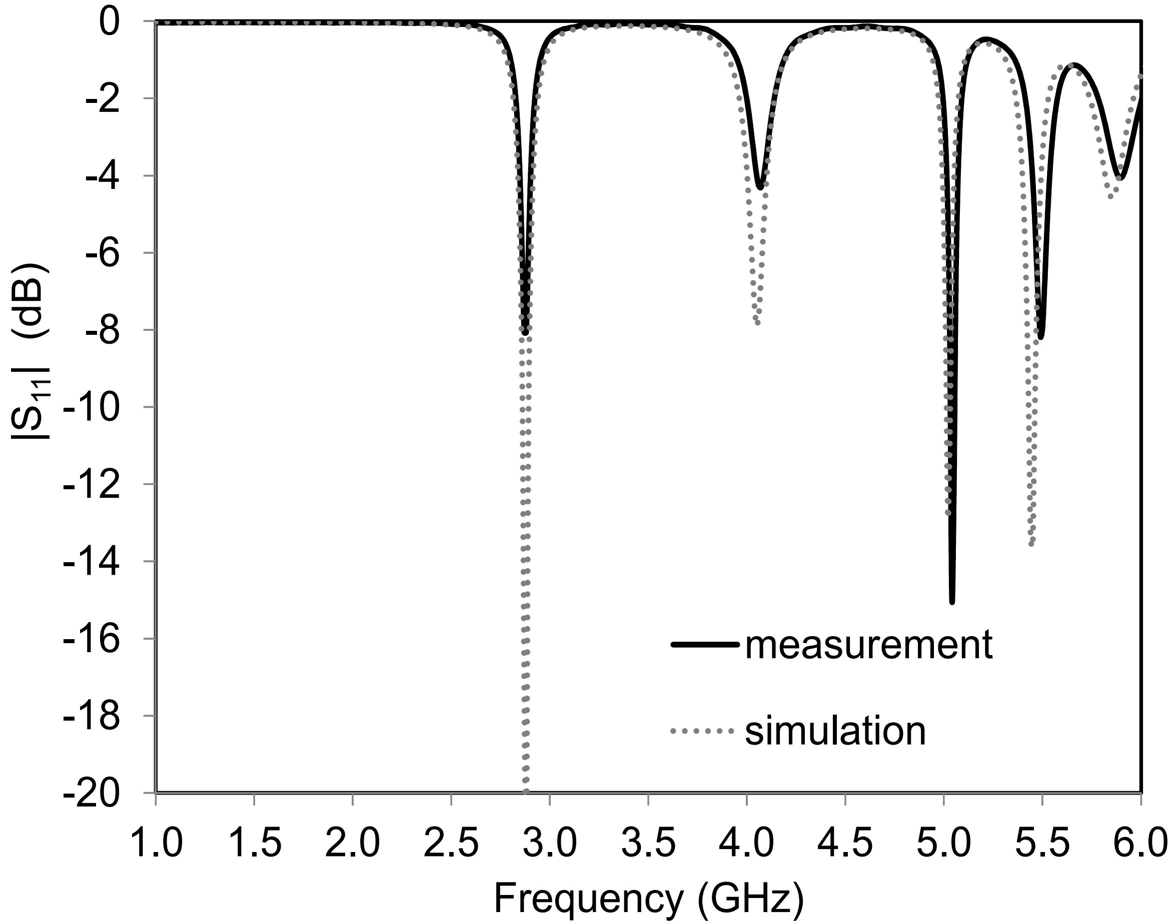
47.2 mm

Metal posts

The substrate is made by t-glase filament, 100% infill percentage, 2 mm thick.

3D-Printed SIW Cavity

The measured $|S_{11}|$ parameter is fitted with the simulation.



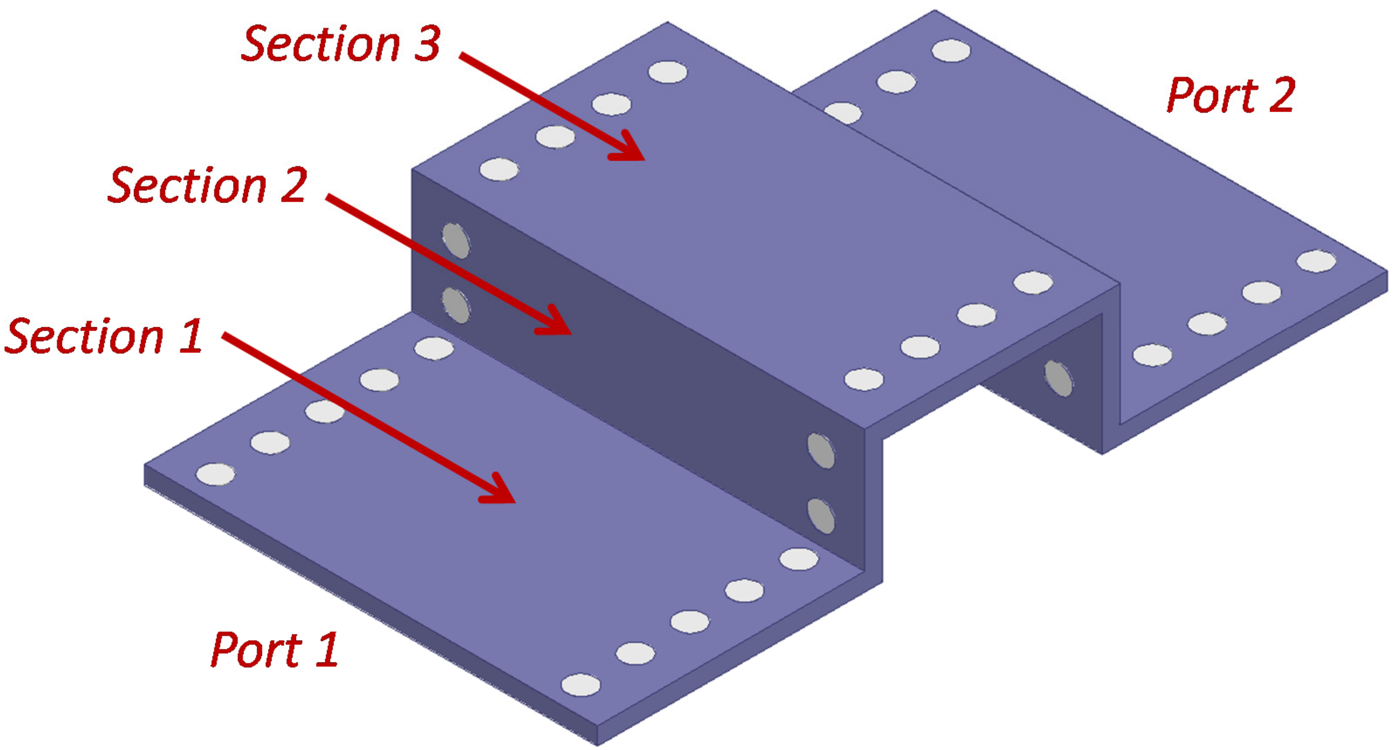
The retrieved dielectric properties for t-glase are:

$\varepsilon_r = 2.3$

$\tan\delta = 0.01$

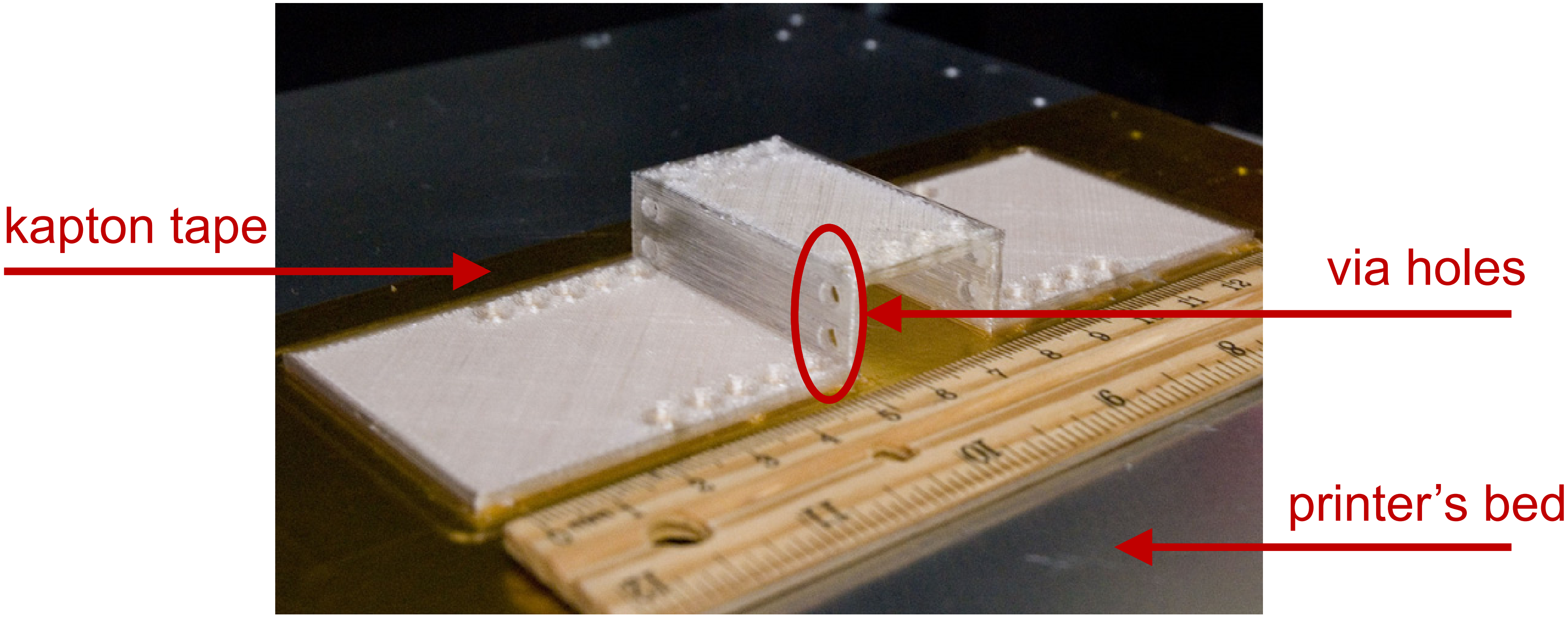
3D-PRINTED SIW STRUCTURE

To **fully exploit the potentiality of 3D printing**, a SIW interconnection with 4 E-plane bends is designed.

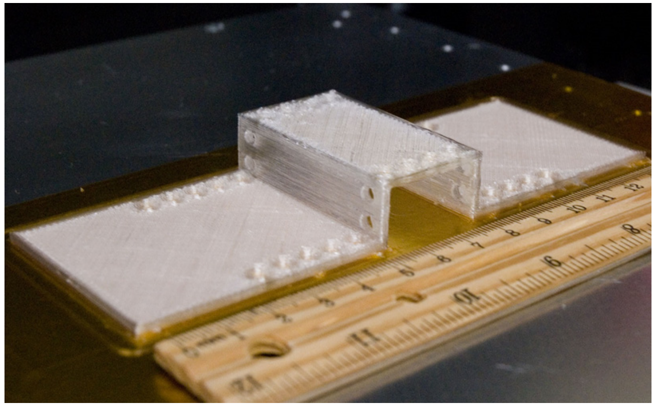


3D-PRINTED SIW STRUCTURE

The structure was printed with t-glase material adopting the Metal Plus 3D printer at 220°C. The cooling system was turned on only during the bridge printing. The metallization of the device is achieved with copper tape and brass rivets inside the via holes.

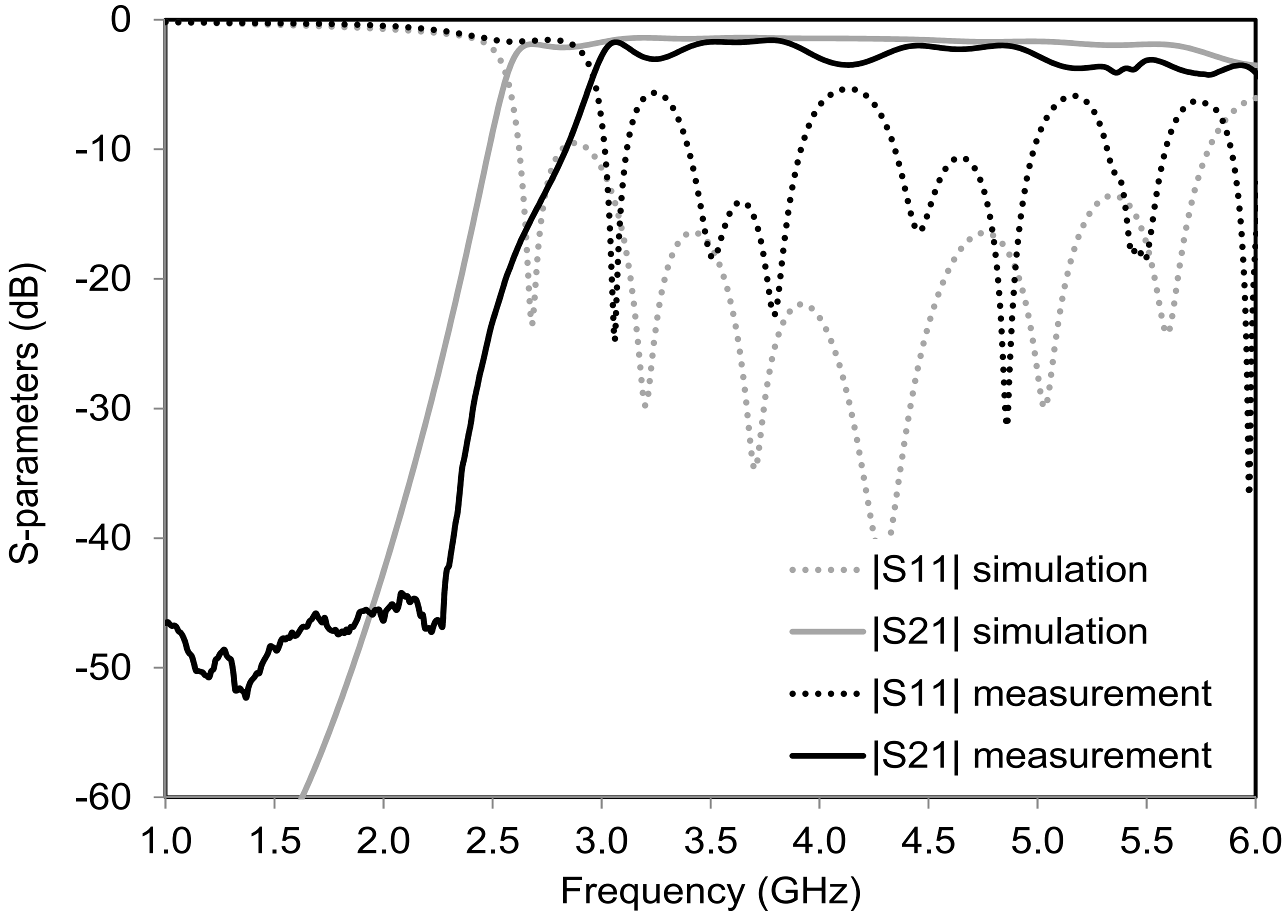


3D-PRINTED SIW STRUCTURE



2.3 dB insertion loss

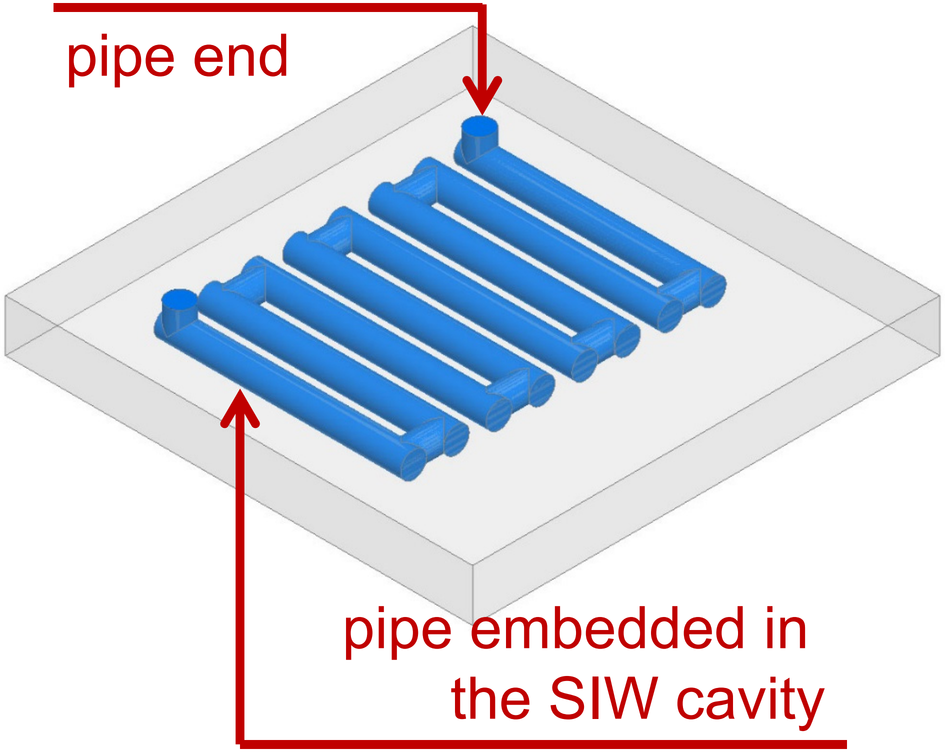
170 MHz shift

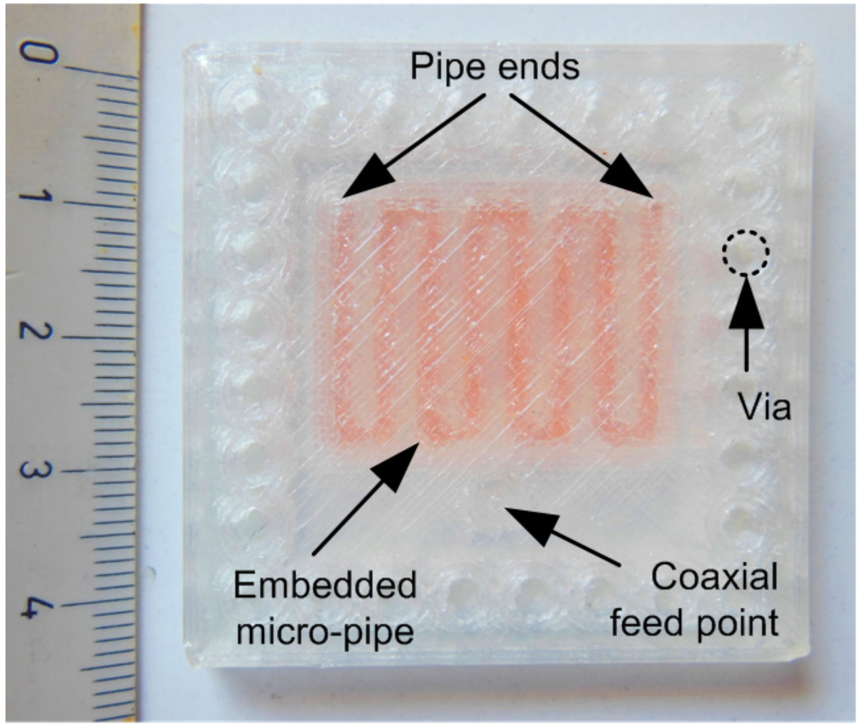


S. Moscato, R. Bahr, T. Le, M. Pasian, M. Bozzi, L. Perregrini, and M.M. Tentzeris, "Additive Manufacturing of 3D Substrate Integrated Waveguide Components," *IET Electronics Letters*, Vol. 51, No. 18, pp. 1426-1428, Sept. 2015.

3D-PRINTED MICROFLUIDIC SENSOR

3D printing and SIW are adopted to design microfluidic sensors. The proposed structure consists of an SIW cavity with an embedded pipe. **Ninjaflex** filament was adopted, to avoid liquid leakage.

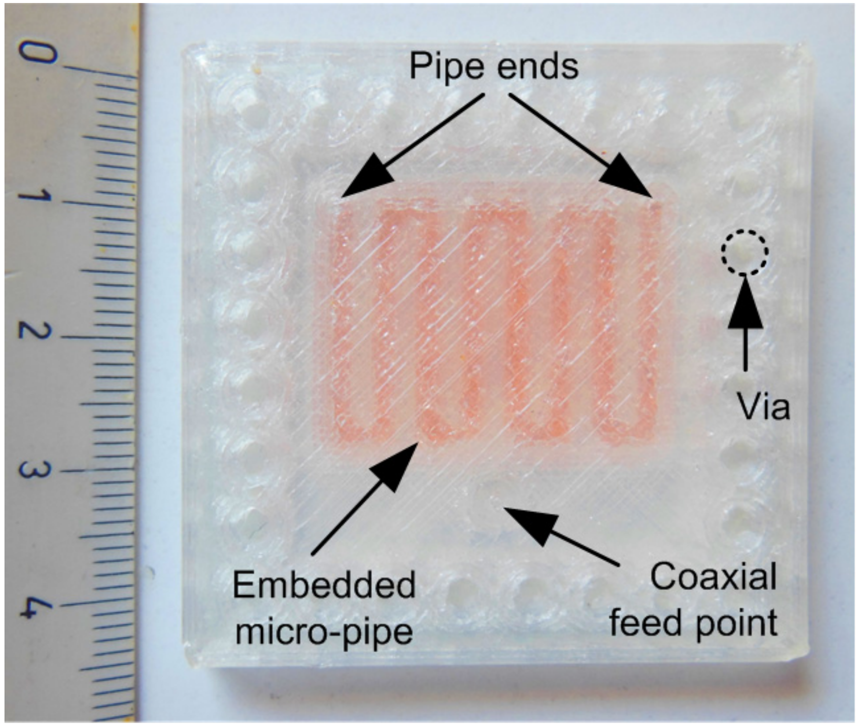


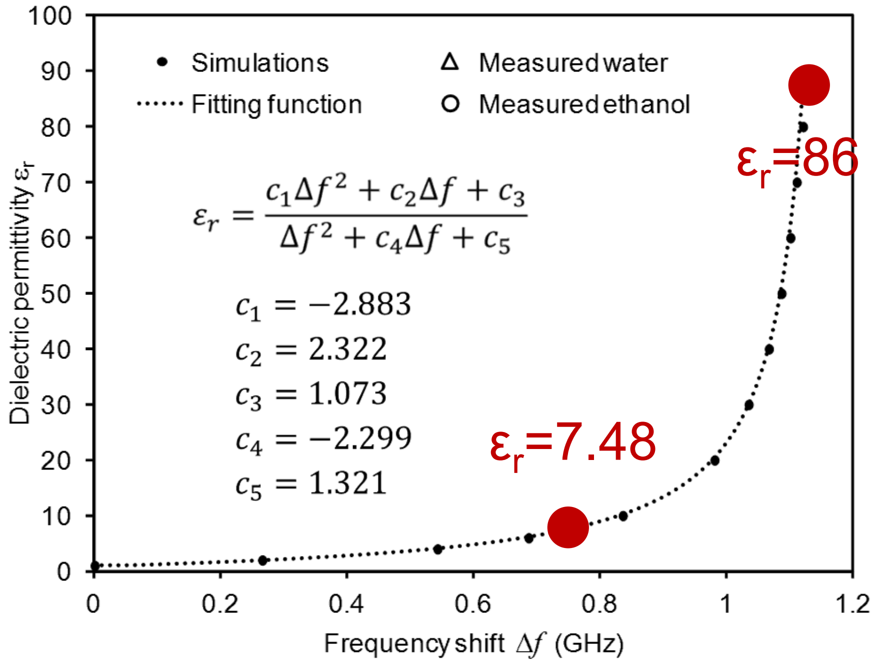


S. Moscato, M. Pasian, M. Bozzi, L. Perregrini, R. Bahr, T. Le, and M. Tentzeris, "Exploiting 3D Printed Substrate for Microfluidic SIW Sensor," *45th European Microwave Conference* (EuMC2015), Paris, France, Sept. 7–10, 2015.

3D-Printed Microfluidic Sensor

The sensor is tested empty, with absolute ethanol (ε_r=7.5) and water (ε_r=80).

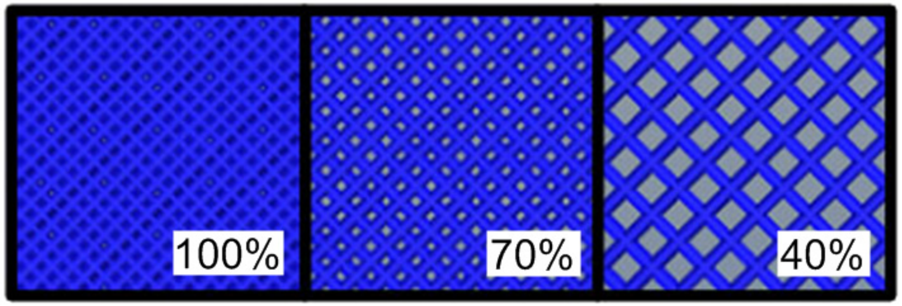




The **sensitivity** can be optimized by properly selecting the length of the pipe.

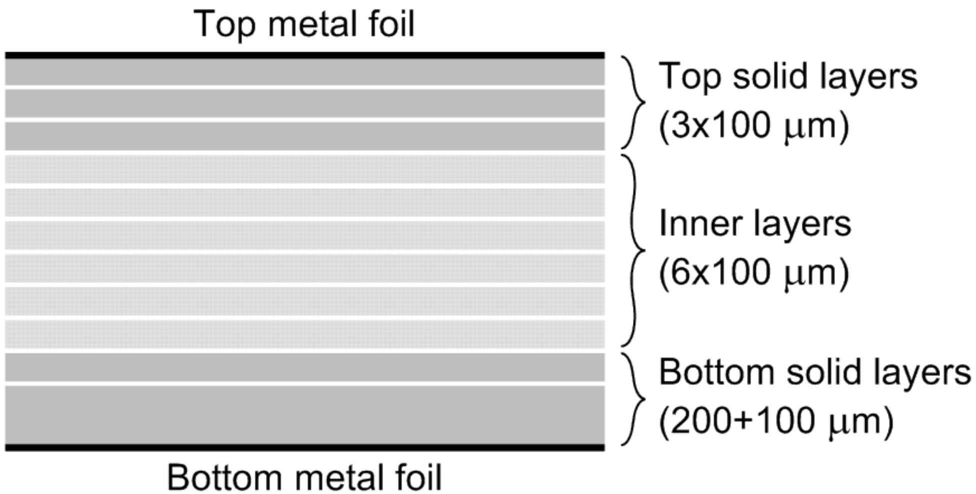
TUNING OF DIELECTRIC PERMITTIVITY

3D printing process allows tuning the dielectric characteristics of substrate materials.



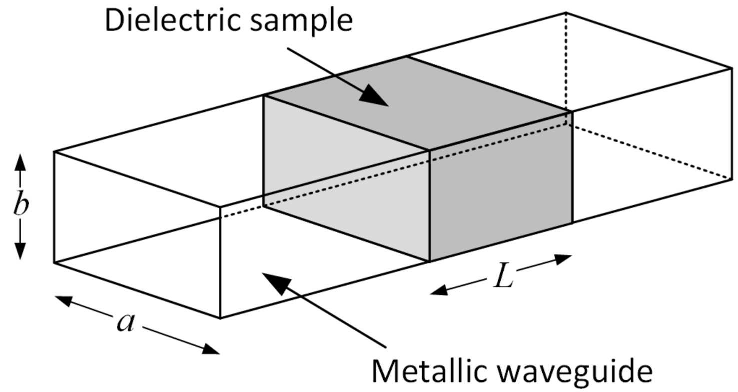
Different **printing patterns** and **filling factors** can be adopted.

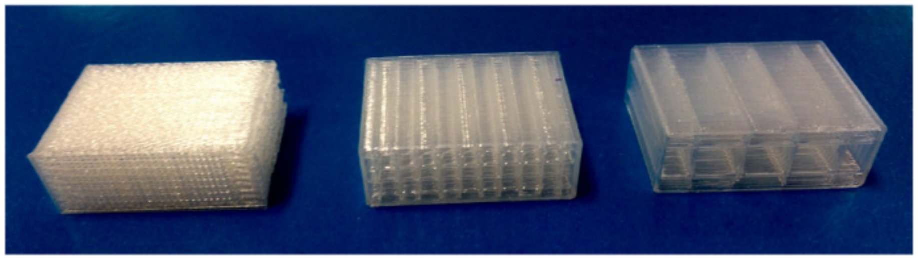
Different **layers** can be printed.

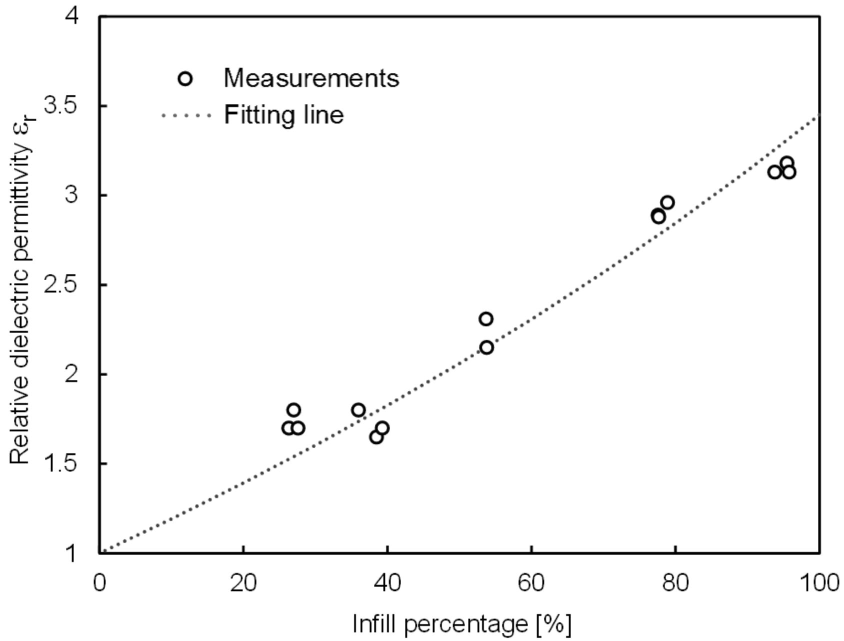


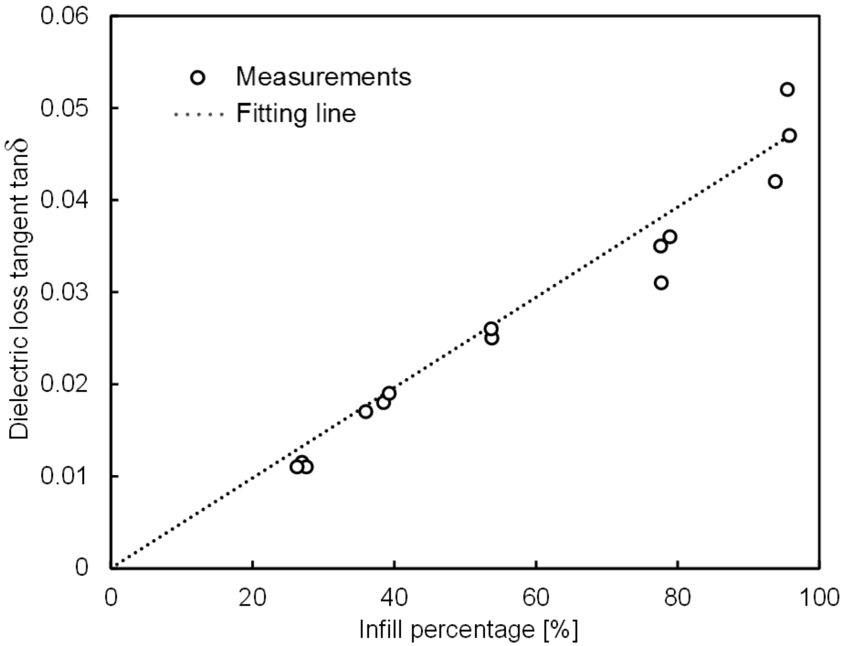
TUNING OF DIELECTRIC PERMITTIVITY

The dielectric permittivity of 3D printed materials with partial infill is estimated by the **Maxwell-Garnett equation**.



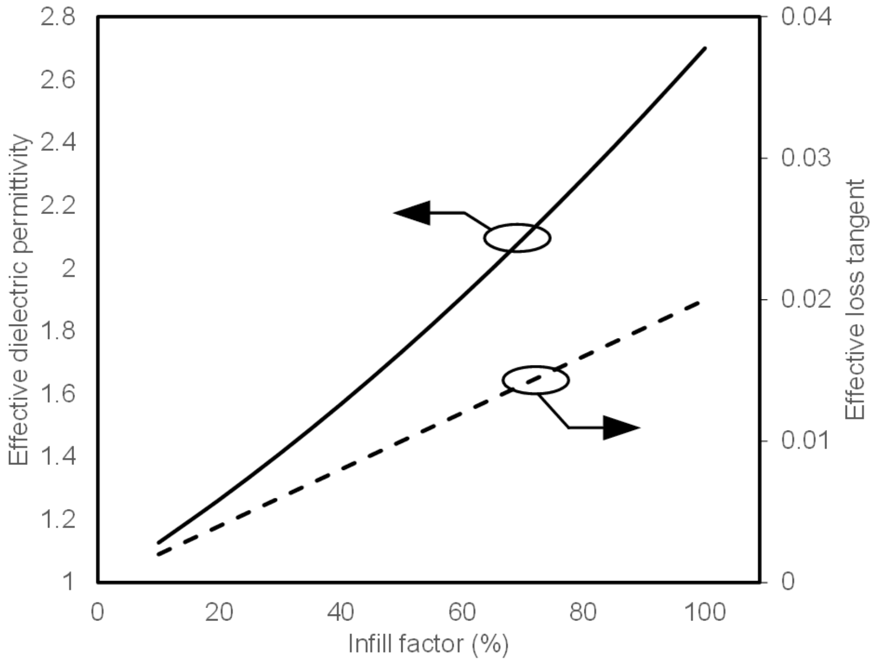


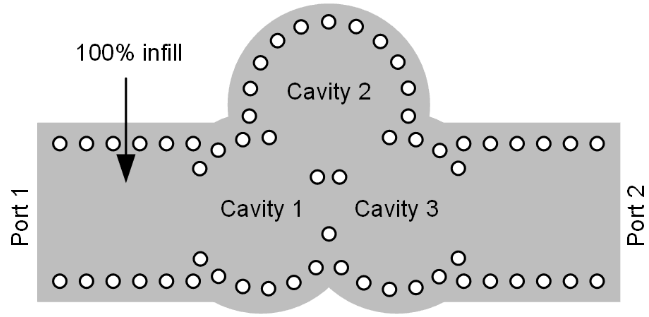




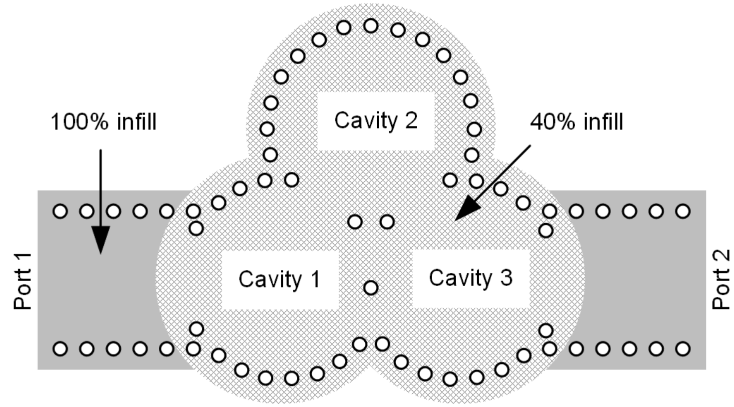
3D Printed SIW Filters

The possibility of tuning the infill factor allows reducing significantly the material loss.





100% infill factor

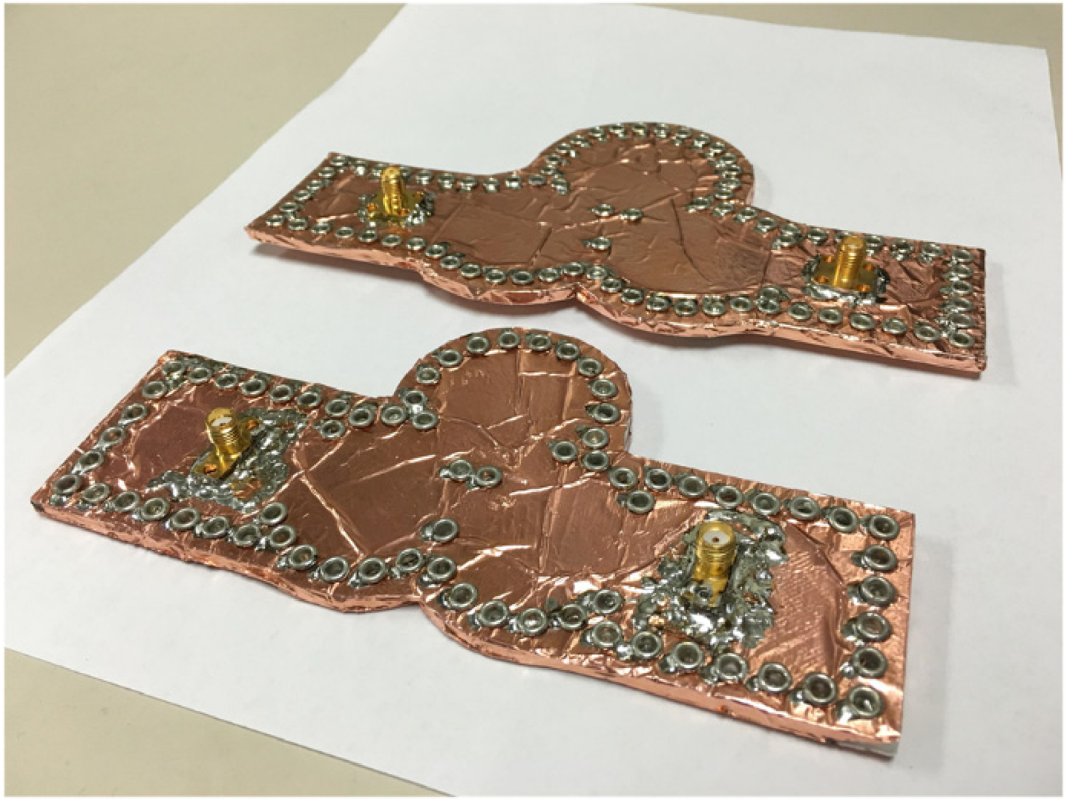


40% infill factor

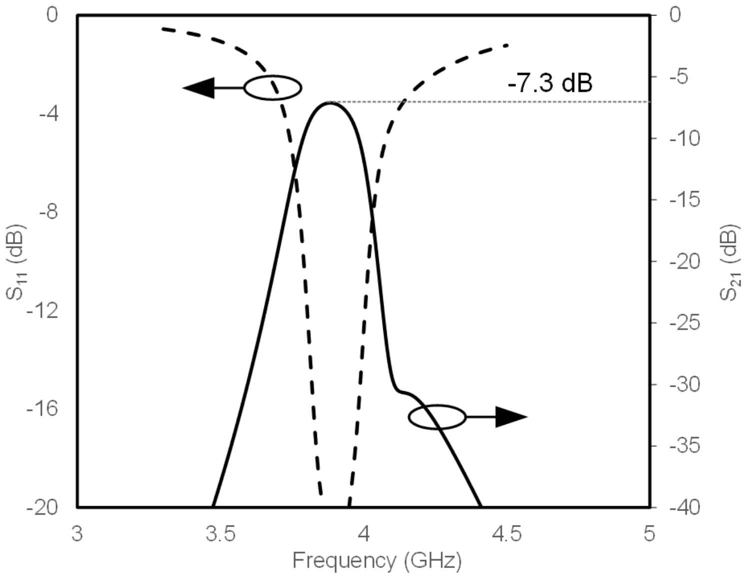
C. Tomassoni, R. Bahr, M. Bozzi, L. Perregrini, and M. Tentzeris, "3D Printed Substrate Integrated Waveguide Filters with Locally Controlled Dielectric Permittivity," 46th European Microwave Conference (EuMC2016), London, UK, Oct. 3–7, 2016.

3D Printed SIW Filters

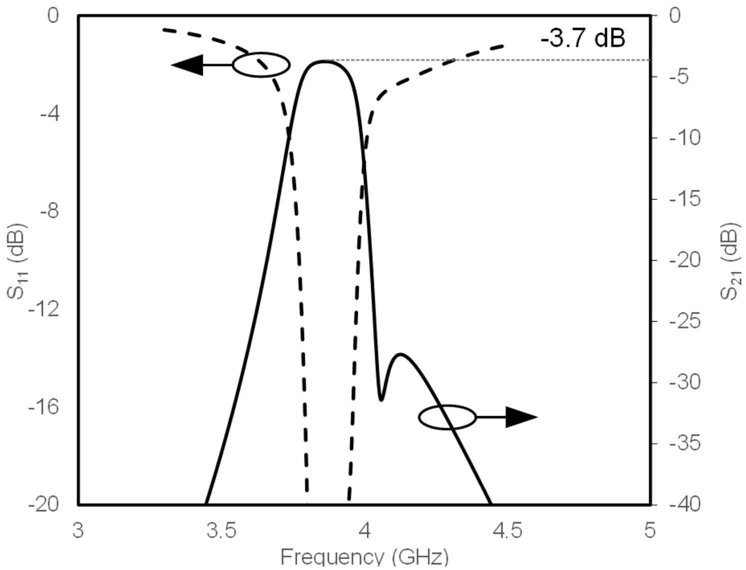
Two filters with the same frequency response and different infill factor have been designed and manufactured. ABS filament was used in this case (ε_r=2.7, tanδ=0.02).



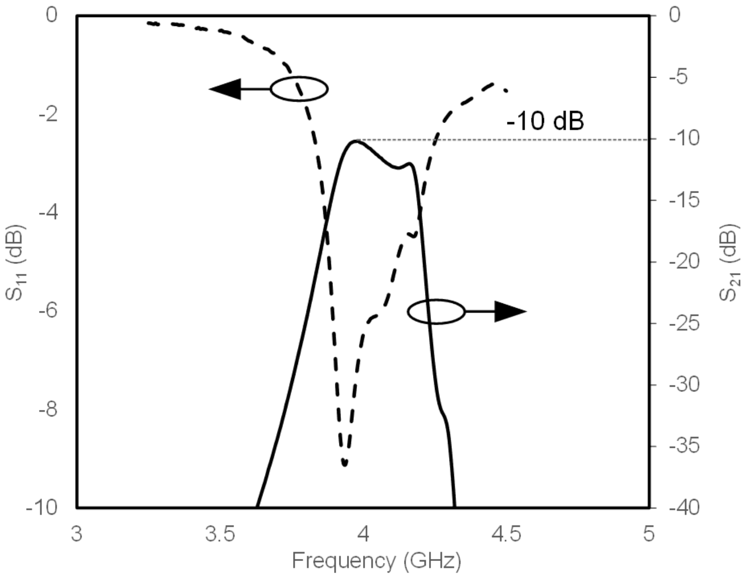
3D PRINTED SIW FILTERS



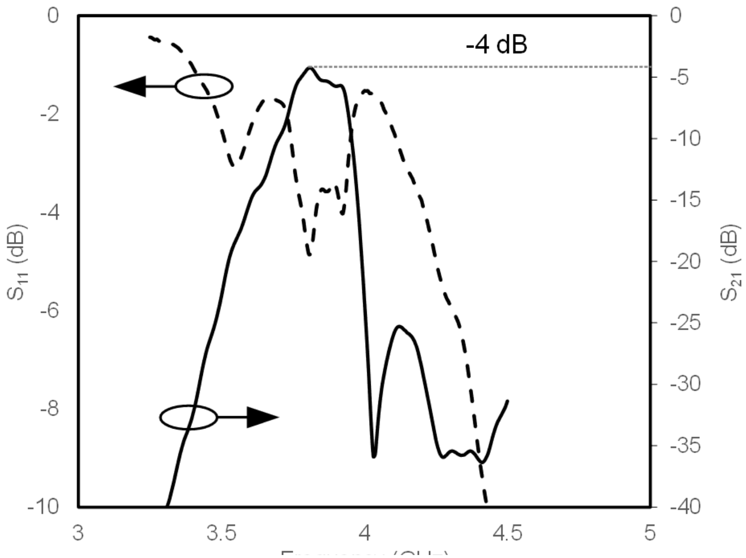
simulation - 100% infill



simulation - 40% infill



measured - 100% infill



measured - 40% infill

ACKNOWLEDGEMENTS

I wish to acknowledge the colleagues who have contributed to the development of this activity:

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- Prof. Ke Wu and his research group (École Polytechnique de Montréal, QC, Canada)
- Prof. Hendrik Rogier and his reasearch group (Ghent University, Belgium)
- Prof. Manos Tentzeris and his reasearch group (Georgia Tech, Atlanta, GA, USA)
- Prof. Cristiano Tomassoni (University of Perugia, Italy)