The AFSIW Technological Platform: The High Performance Millimeter-Wave PCB Alternative

« Honey, I Shrunk the Circuit »

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Outline

- Motivation
- The Substrate Integrated Waveguide (SIW) Technology
- The Air-filled SIW (AFSIW) Technological Platform
- Focus on AFSIW Filters for the New Space Applications
- Conclusion and Perspective

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Motivation

www.afsiw.com

Progress in Electronics

Advances in electronics:

- Sustain our societal development,
- Provide an increasing number of functionalities to anyone, anywhere, at any time.

Technologies are rapidly evolving

It is not because you are today one of the major actors that you will survive

Some good exemples of « *has been* » leading high tech players are for instance *Nokia and Blackberry*

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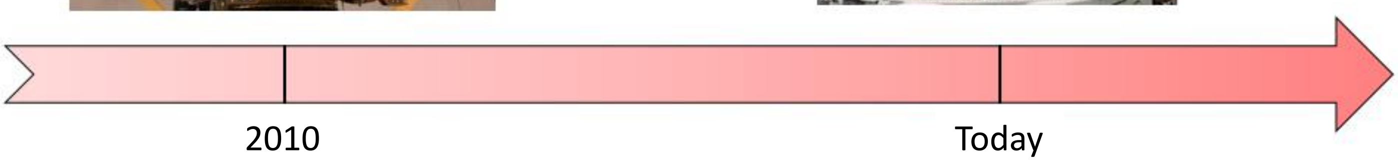
Progress in Electronics for Space

Change of paradigm in the space industry:

1 launcher for 1 massive dedicated satellite

1 reusable launcher for 60 reconfigurable stacked satellites



The progress in the space industry is going more rapidly than ever

The New Space Revolution Is Comming !

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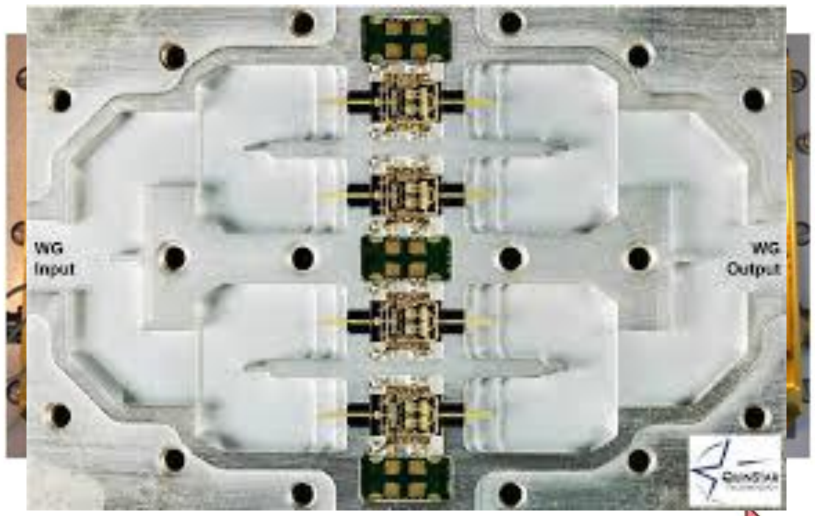
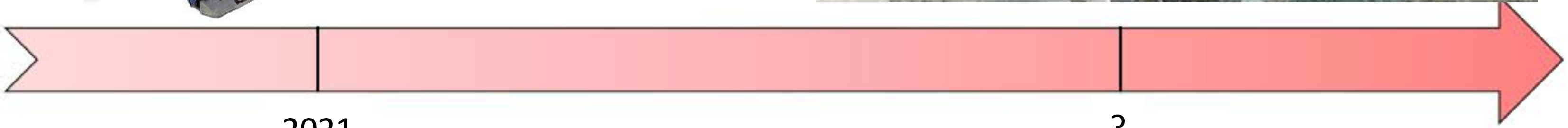
Progress in Electronics for Space

TWTA

SSPA

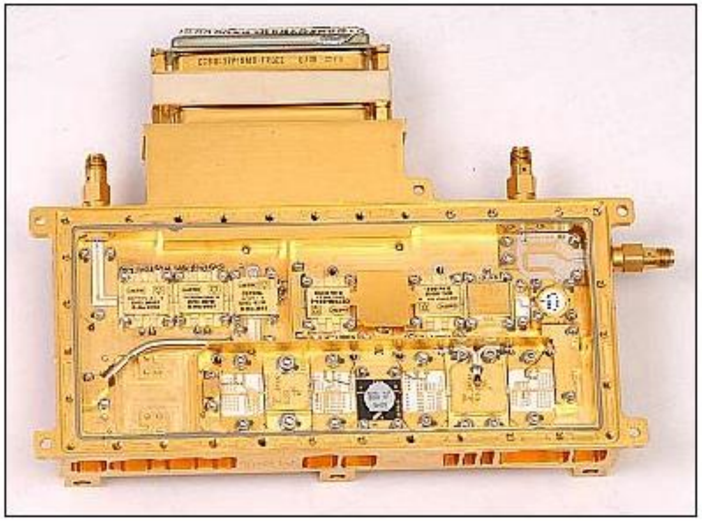




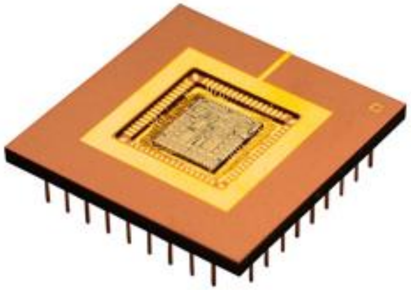
Integration and multi-functionality is the trend for the design of versatile systems

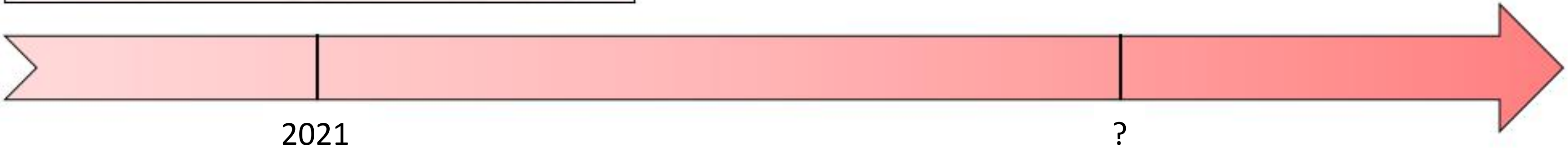
Progress in Electronics for Space

AsGa MMIC Modules



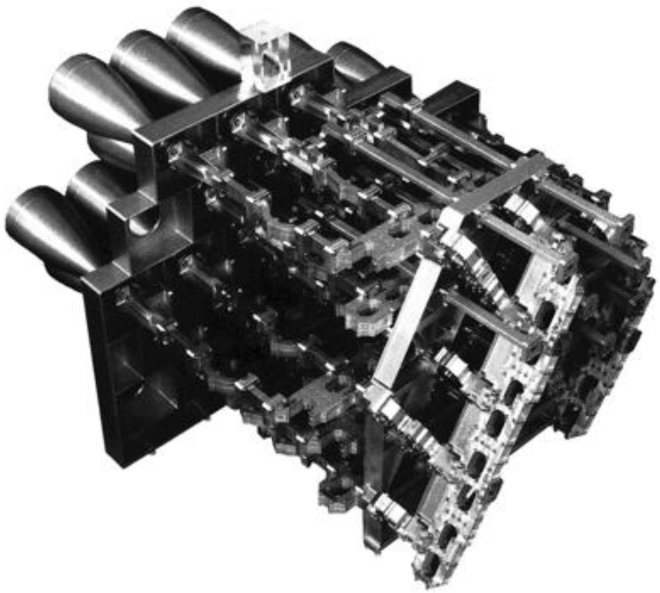
Monolithic Silicon RFIC





Integration and multi-functionality is the trend for the design of versatile systems

Progress in Electronics for Space



?

Integration and multi-functionality is the trend for the design of versatile systems

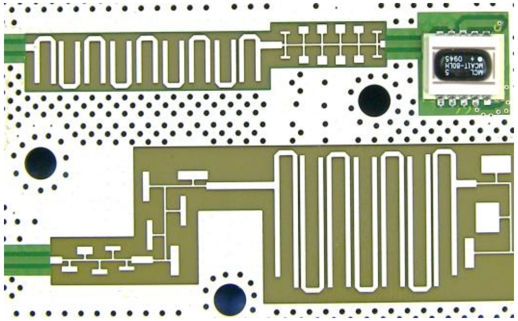
Planar and Waveguide Technologies Conflicting Paradigms

Air-Filled Waveguide (1893)

- Low insertion loss
- High quality factor
- Self shielded
- High power handling

- High cost
- Not integrated
- High weight
- Complex manufacturing

Printed Circuit Boards (1952)



- High insertion loss
- Low quality factor
- Shielding is mandatory
- Low power handling
- PFAS

- Low cost
- High integration density
- Low weight
- Standard manufacturing

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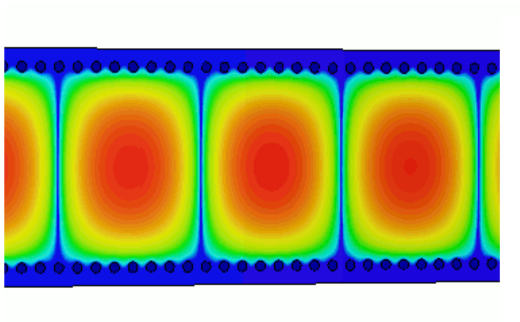
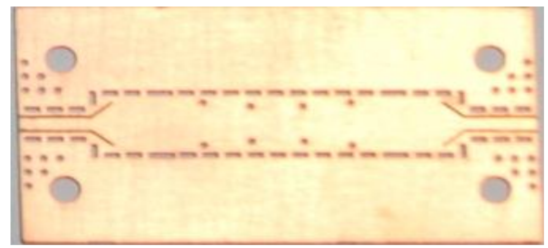
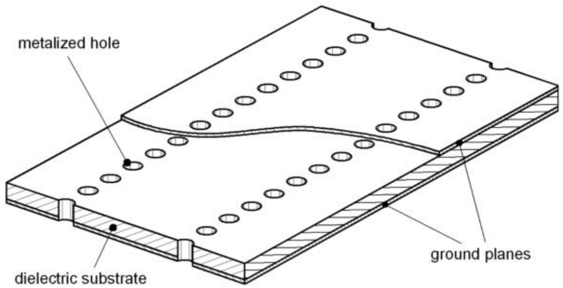
Substrate Integrated Waveguide Alternative Technological Plateform

SIW
(2000)



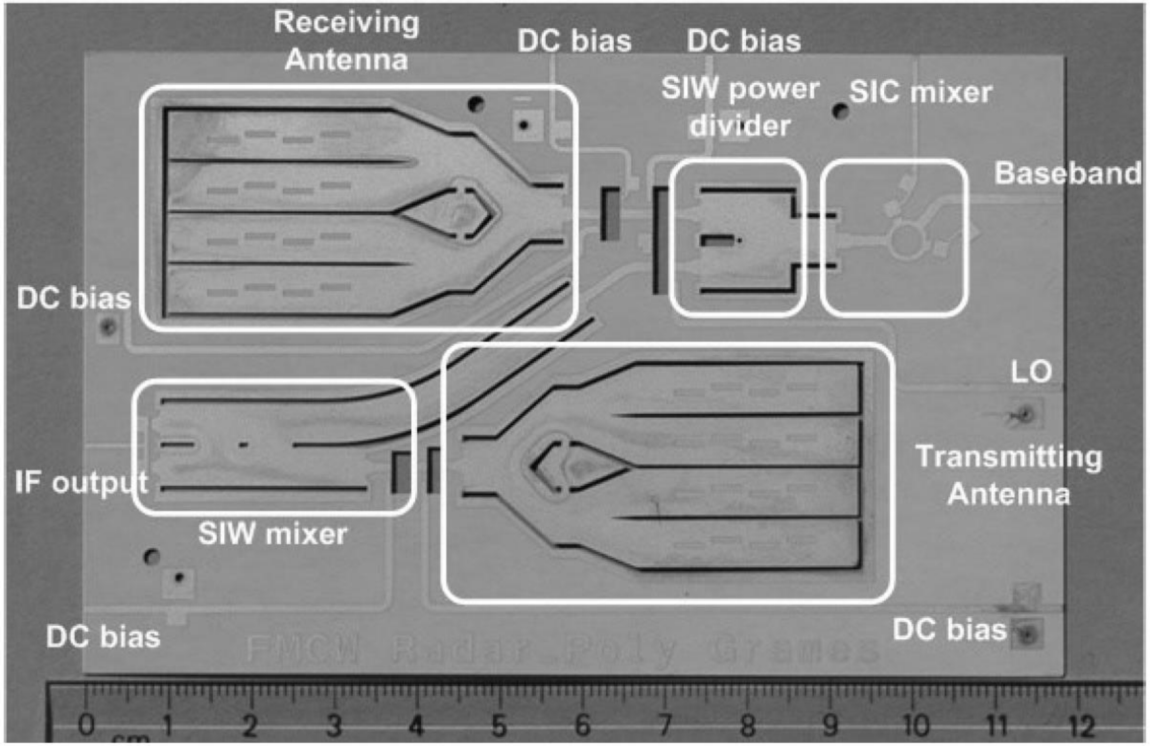




- Low cost
- High integration density
- Low weight
- Self shielded
- Medium insertion loss
- Medium quality factor
- Medium power handling
- PFAS

SIW popular implementation: discontinuous sidewalls

Substrate Integrated Waveguide Alternative Technological Plateform

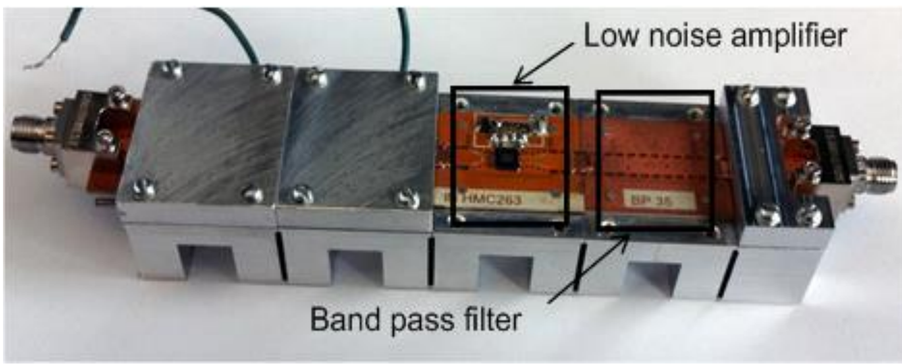


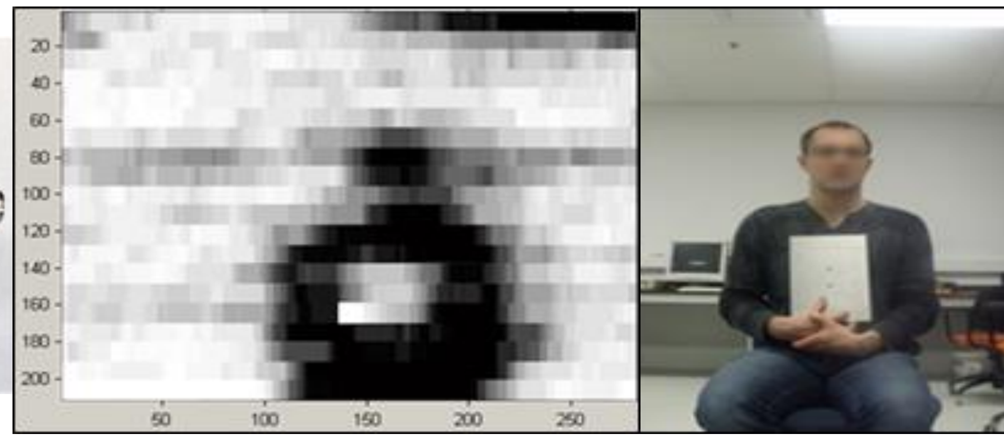
Z. Li and K. Wu,“24-GHz Frequency-Modulation Continuous-Wave Radar Front-End System-on-Substrate,” IEEE Trans. On Microwave Theory and Techniques, Vol.56, No.2, pp.278-285, Feb. 2008.

SIW alternative implementation: continuous sidewalls

Substrate Integrated Waveguide Alternative Technological Plateform

Exemple of an SIW Passive Imaging Receiver operation at Ka-Band





A. Doghri, A. Ghiotto, T. Djerafi and K. Wu, "Early demonstration of a passive millimeter-wave imaging system using substrate integrated waveguide technology," 11th IEEE Mediterranean Microwave Symposium, Hammamet, Tunisia, 08-10 Sept. 2011.

High performance applications need an alternative

Back in 2012

Grenoble

Bordeaux

Anthony, SIW is too lossy ! What to do ?

I actually have an idea but it sound out of **one** mind ☹

Let me introduce you Frédéric
It may not be out of **two** minds ! ☺

☺☺☺

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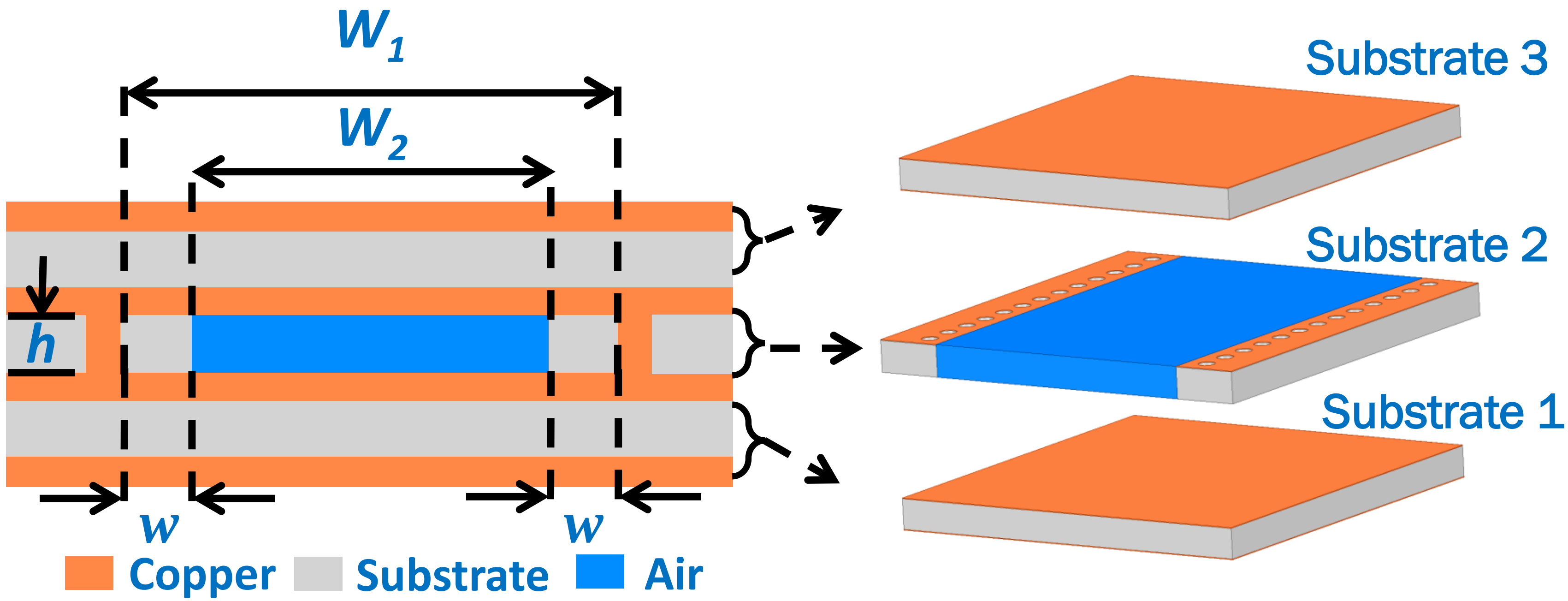
Air-Filled Substrate Integrated Waveguide Alternative Technological Plateforms

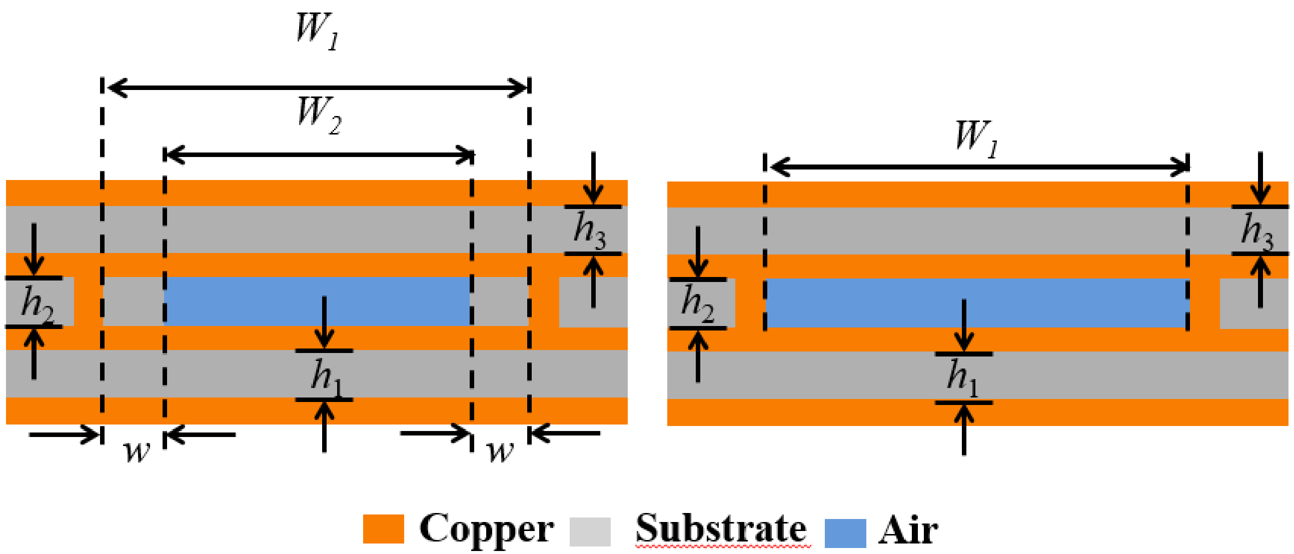
Air-Filled SIW (2014)[1]



High degrees of freedom leading to creative designs

[1] F. Parment, and Al., "Broadband transition from dielectric-filled to air-filled Substrate Integrated Waveguide for low loss and high power handling millimeter-wave Substrate Integrated Circuits," *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*, Tampa, FL, 2014, pp. 1-3.

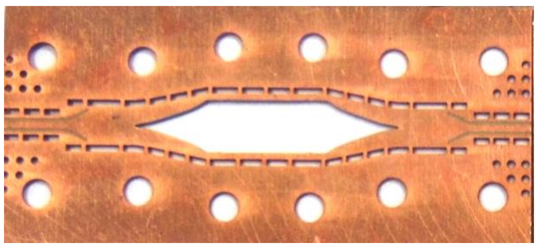
Air-Filled Substrate Integrated Waveguide Alternative Technological Plateforms

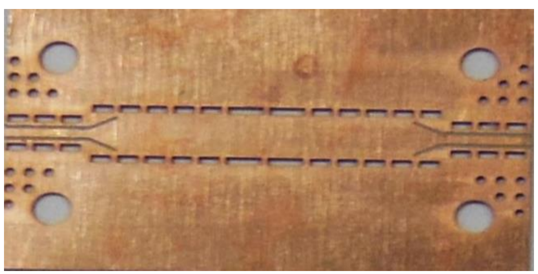


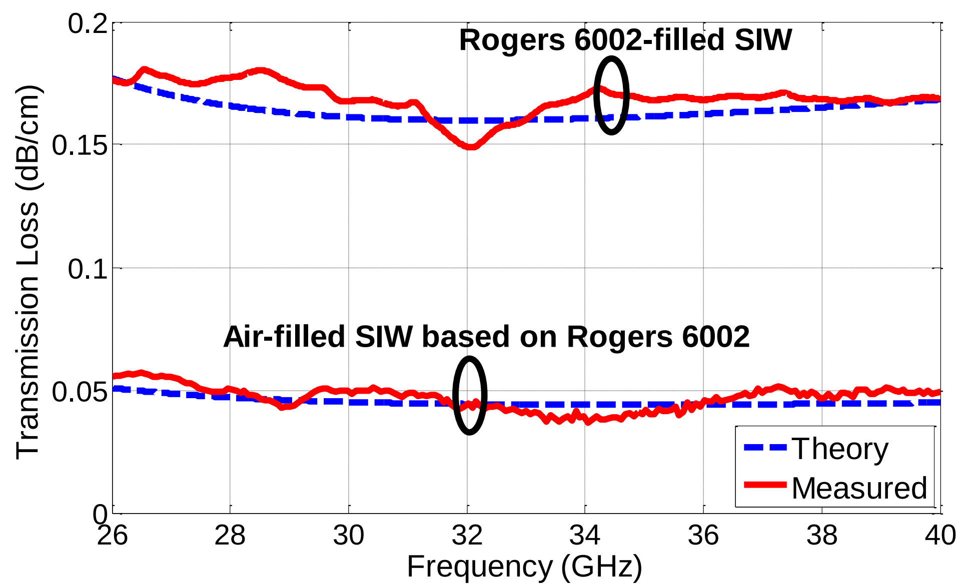
As for SIW, discountinous and/or continuous sidewalls are implementable

$$\alpha = \alpha_d + \alpha_{c+r}$$

- α_d : dielectric losses → $= 0$
- α_{c+r} : conduction losses + surface roughness → $\alpha_{c+r} = \alpha_c * K_{Hammerstad}$







→ **Significant loss reduction compared to SIW**

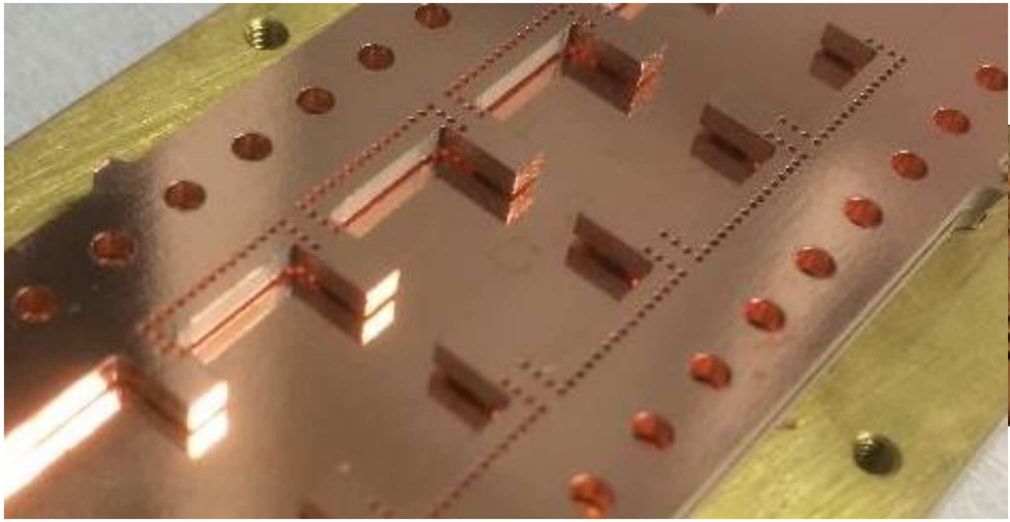
F. Parment, A. Ghiotto, T.P. Vuong, J.M. Duchamp, and K. Wu, "Air-filled substrate integrated waveguide for low loss and high power handling millimeter-wave substrate integrated circuits," IEEE Trans. Microw. Theory Techn., vol. 63, no. 4, pp. 1-11, Apr. 2015.

	6002-filled SIW	5880-filled SIW	AFSIW
Dielectric loss (dB/cm)	0.081	0.052	0
Ohmic loss (dB/cm)	0.053	0.045	**0.029**
Surface roughness loss (dB/cm)	0.026	0.022	**0.014**
Total loss (dB/cm)	0.16	0.12	**0.044**
Q-factor	187	251	**680**
APHC (dBm)	47.2	46.8	**54.8**
PPHC (kW)	1046	2375	**23.6**
Width (mm)	4.11	4.77	**7.04**

F. Parment, A. Ghiotto, T.P. Vuong, J.M. Duchamp, and K. Wu, "Air-filled substrate integrated waveguide for low loss and high power handling millimeter-wave substrate integrated circuits," IEEE Trans. Microw. Theory Techn., vol. 63, no. 4, pp. 1-11, Apr. 2015.

Examples of creative designs taking advantage of the **dielectric slab sidewalls**

- Phase shifter [2]
- Compensated phase shifter [3]
- Thermally compensated filter [4]



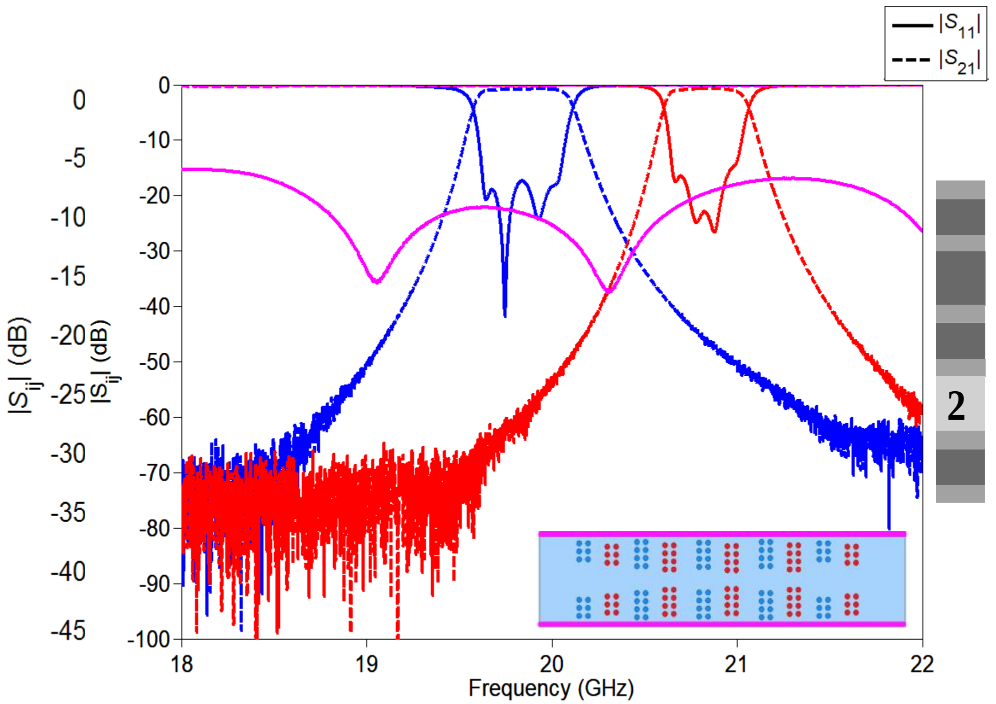
[2] F. Parment, A. Ghiotto, T.P. Vuong, J.M. Duchamp, K. Wu, "Air-filled SIW transmission line and phase shifter for high performances and low-cost U-band integrated circuits and systems," *8th IEEE Global Symposium on Millimeter-Waves*, Montreal, 25-27 May. 2015.

[3] F. Parment, A. Ghiotto, T.P. Vuong, J.M. Duchamp, and K. Wu, "Double dielectric slab-loaded air-filled SIW phase shifters for high-performance and low-cost millimeter-wave integration," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no .9, pp. 2833-2842, Sept. 2016.

[4] T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

Examples of creative designs taking advantage of the **multilayer characteristic**

- Compact bandpass filter [5]
- Post-process tuning [6]
- Configurable transmission line [7]

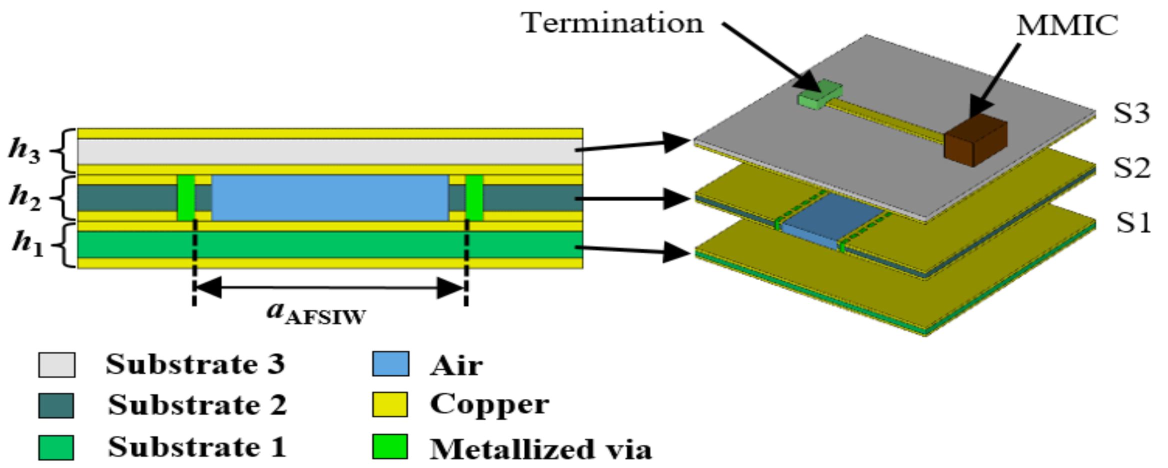


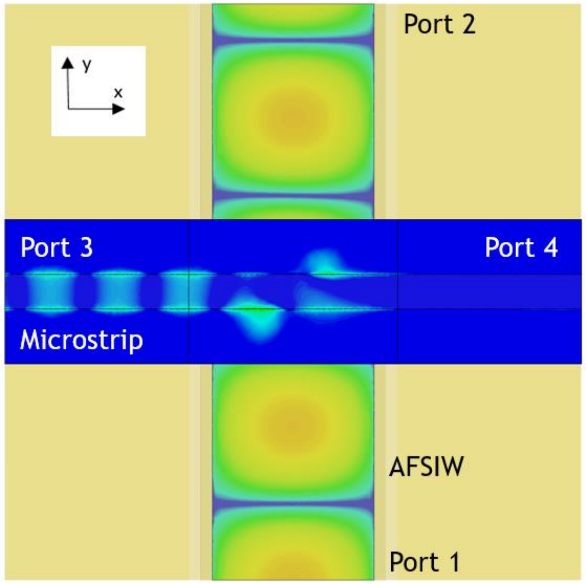
[5] F. Parment, A. Ghiotto, T.P. Vuong, J.M. Duchamp, and K. Wu, "Ka-band compact and high performance bandpass filter based on multilayer air-filled SIW," in *IET Electronics Letters*, vol. 53, no .7, pp. 486-488, Mar. 2017.

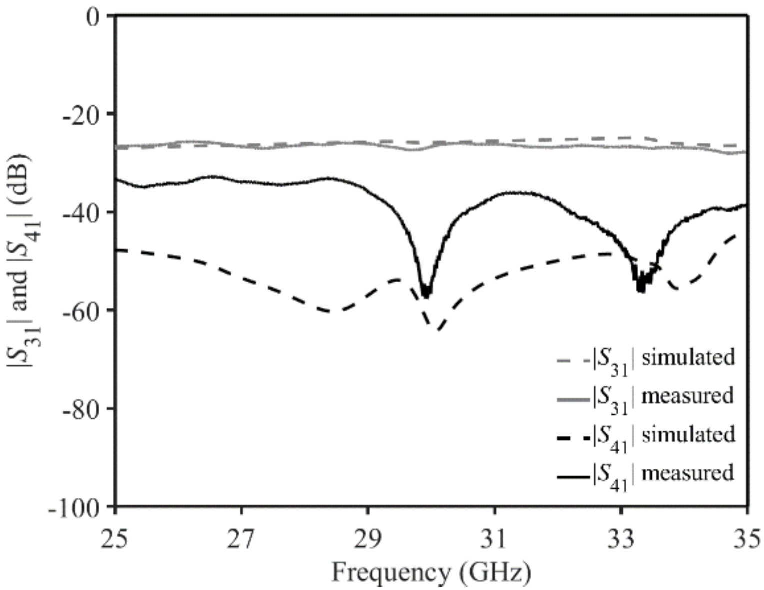
[6] T. Martin, A. Ghiotto, T.P. Vuong, F. Lotz and P. Monteil, "High performance air-filled substrate integrated waveguide filter post-process tuning using capacitive post," 2017 *IEEE MTT-S International Microwave Symposium*, Hawaii, Honolulu, 4-9 Jun. 2017, pp. 196-199.

[7] T. Martin, A. Ghiotto, F. Lotz and T. Vuong, "Fabrication-tolerant reconfigurable AFSIW filters based on through-hole mounted metallic posts for versatile high performance systems," *2018 IEEE/MTT-S International Microwave Symposium - IMS*, Philadelphia, PA, 2018, pp. 319-322.

AFSIW - Multilayer directional coupler







A. Ghiotto, J.-C. Henrion, T. Martin, J.-M. Pham, and V. Armengaud, "AFSIW-to-Microstrip Directional Coupler for High-Performance Systems on Substrate," IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, 2020.

AFSIW - Circulator

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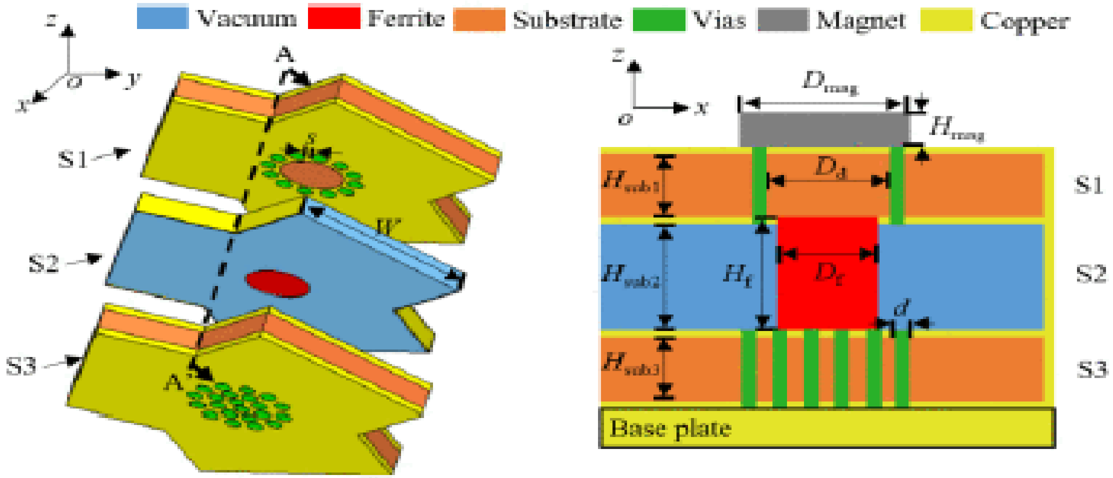
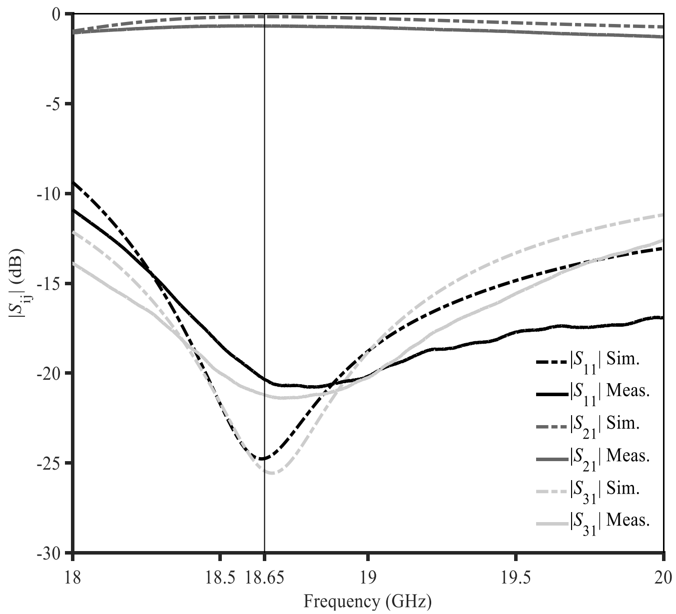
www.afsiw.com





- 18 to 20 GHz
- 0.68 dB IL (using FR4)
- Isolation better than 14dB

I. Marah, A. Ghiotto, A. Verger, and J. -M. Pham, "AFSIW Y-junction Circulator for High-power Handling New Space Applications," IEEE/MTT-S International Microwave Symposium (IMS), Denver, CO, USA, 2022.

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  - Filtering functions challenges
- Conclusion and Perspective

Filter Challenges

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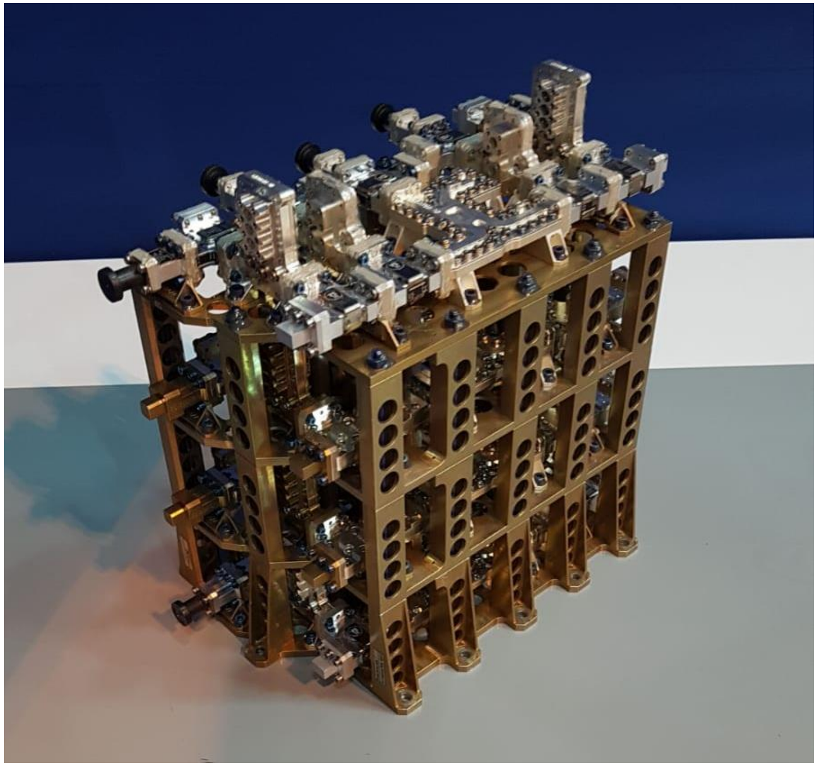
- Satellite payload configuration need MUX
- IMUX are critical in terms of mass and volume
- Satellite constellations require low SWaP-C MUX

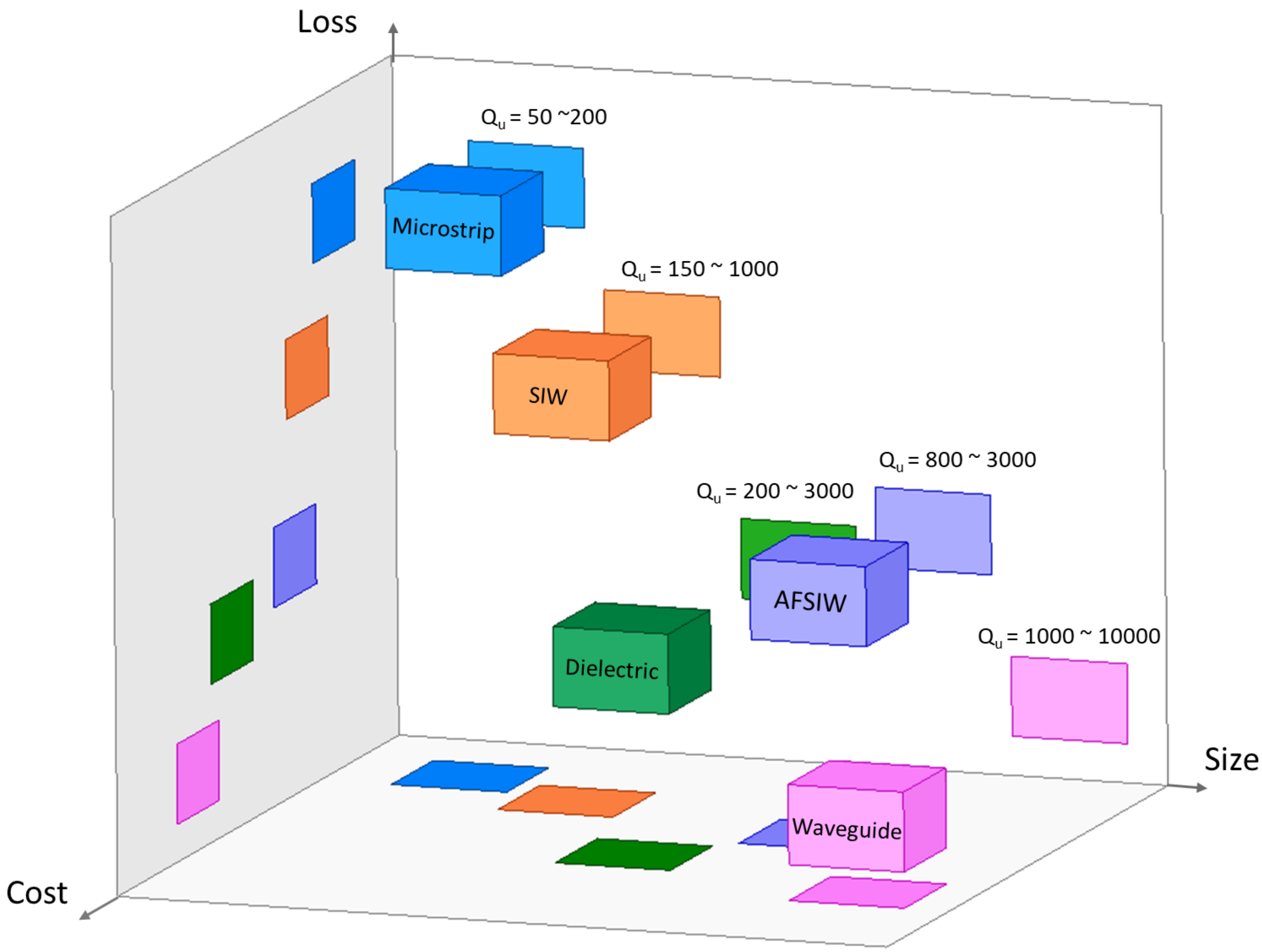
- Objective is to reduce mass and volume, at an affordable cost, while maintaining high performances

- It is necessary to introduce a new technology



Courtesy of Thales Alenia Space

Resonator Technologies



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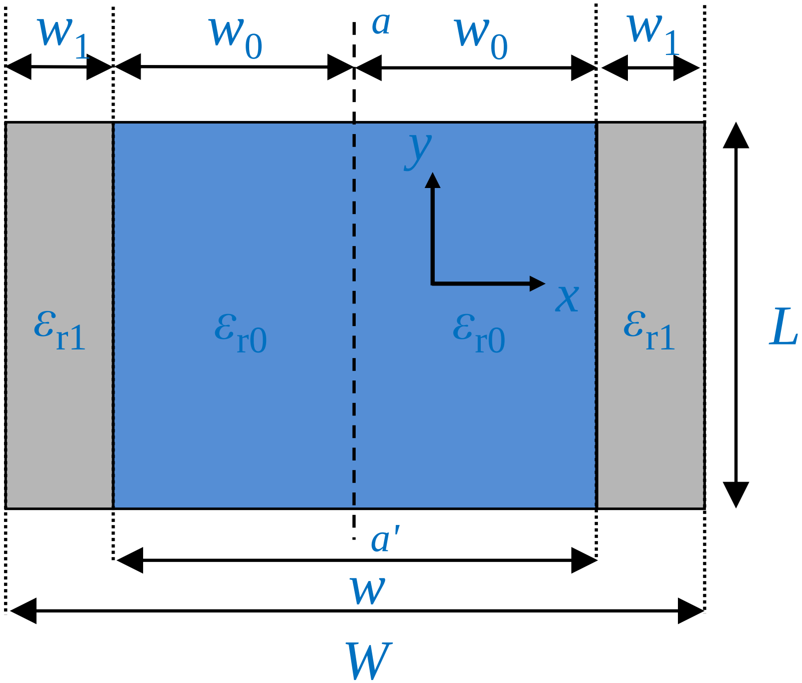
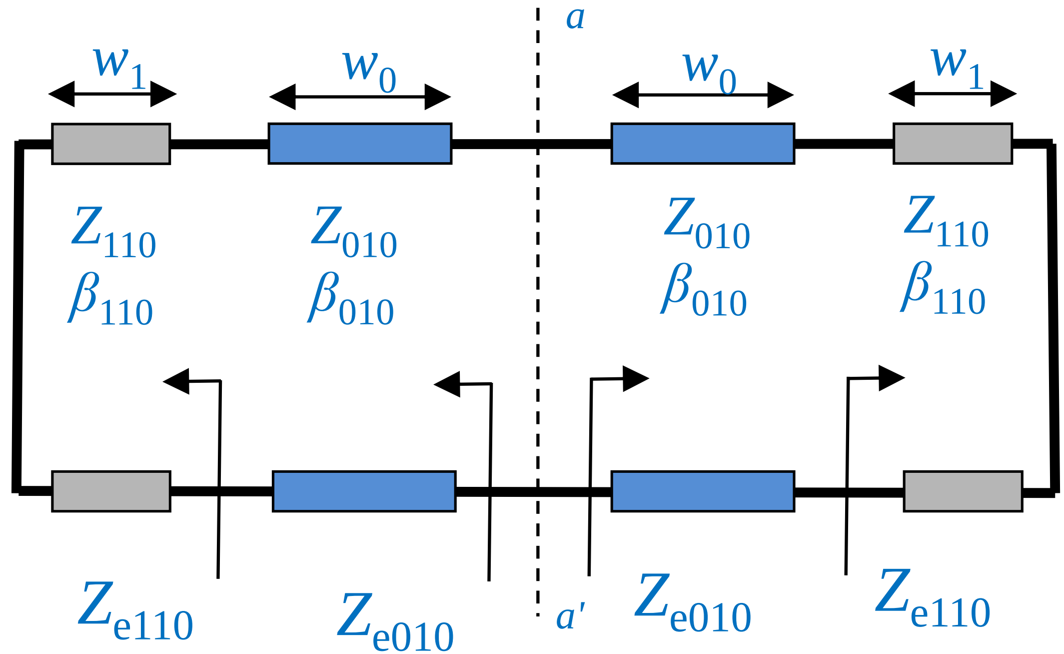
PATENTED

Temperature Compensation Principle

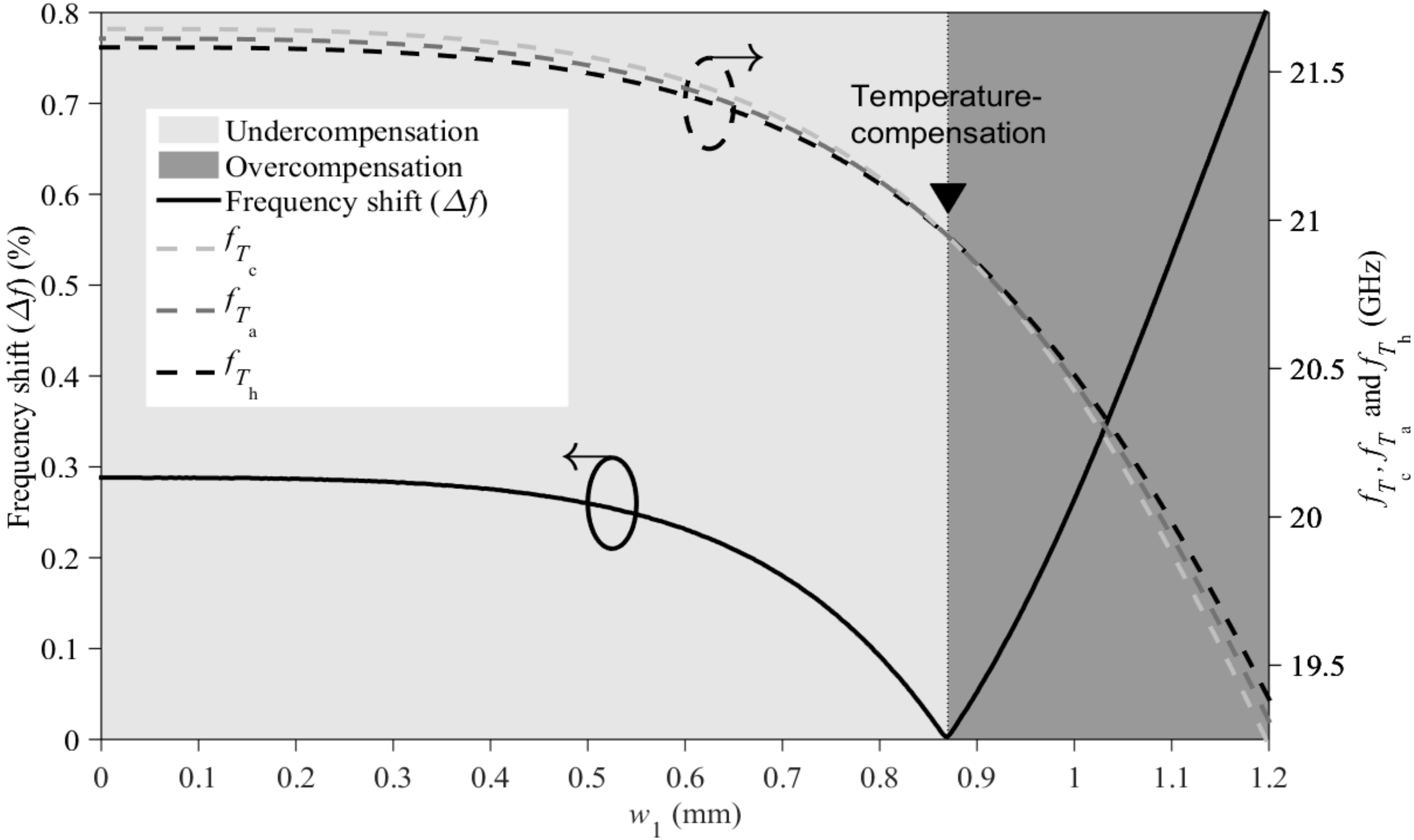




- Multiphysics model (mechanical, thermal and electromagnetics)
- Characteristic equation
  - Resonant frequency
  - AFSIW cavity dimensions
  - Material electromagnetic properties

T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

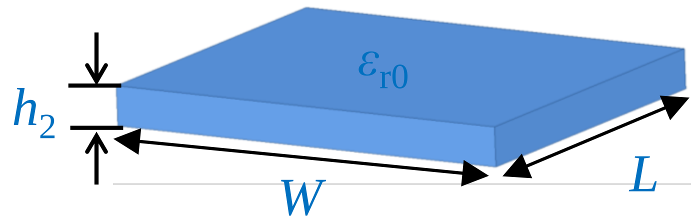
Theoretical Analysis



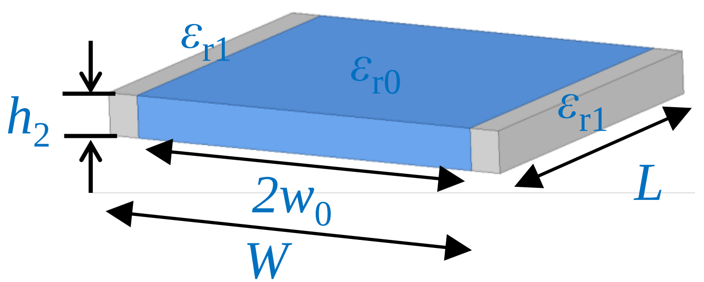
T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

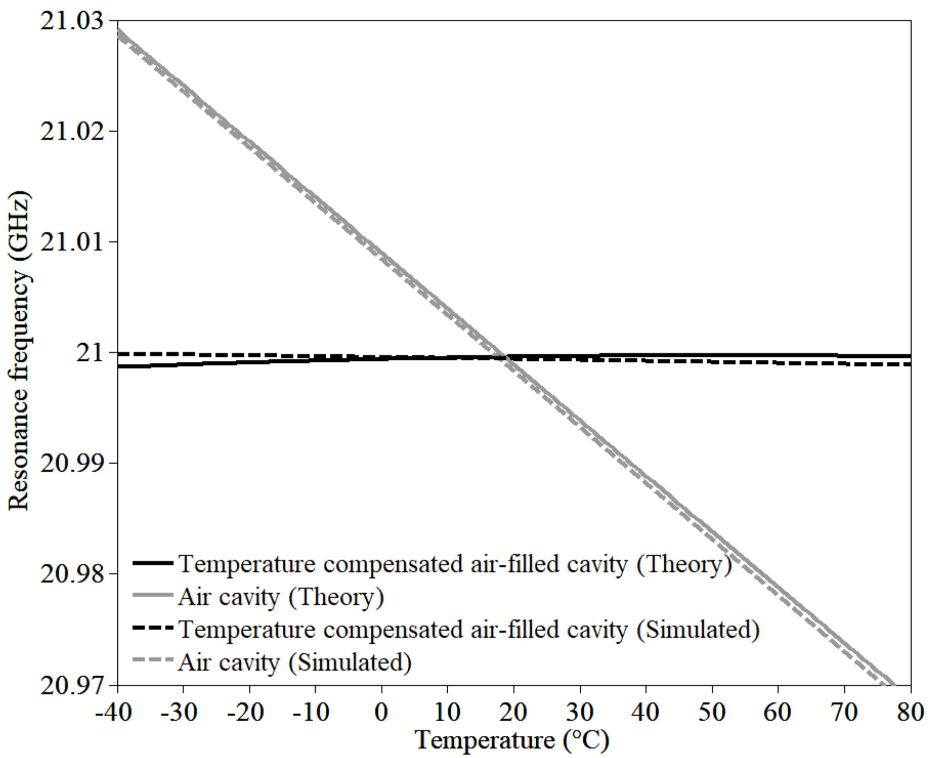
Theoretical Model vs Eigenmode Simulations

Air cavity



Double slab air-filled cavity

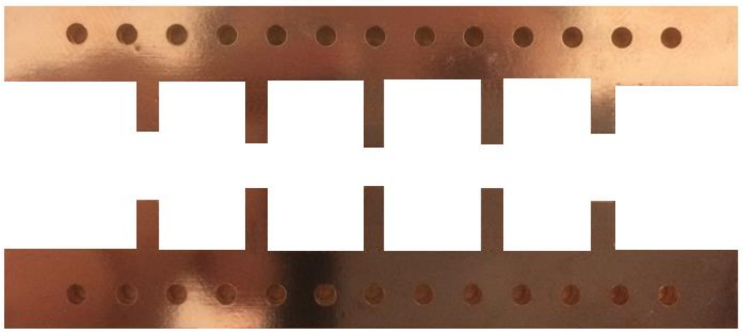


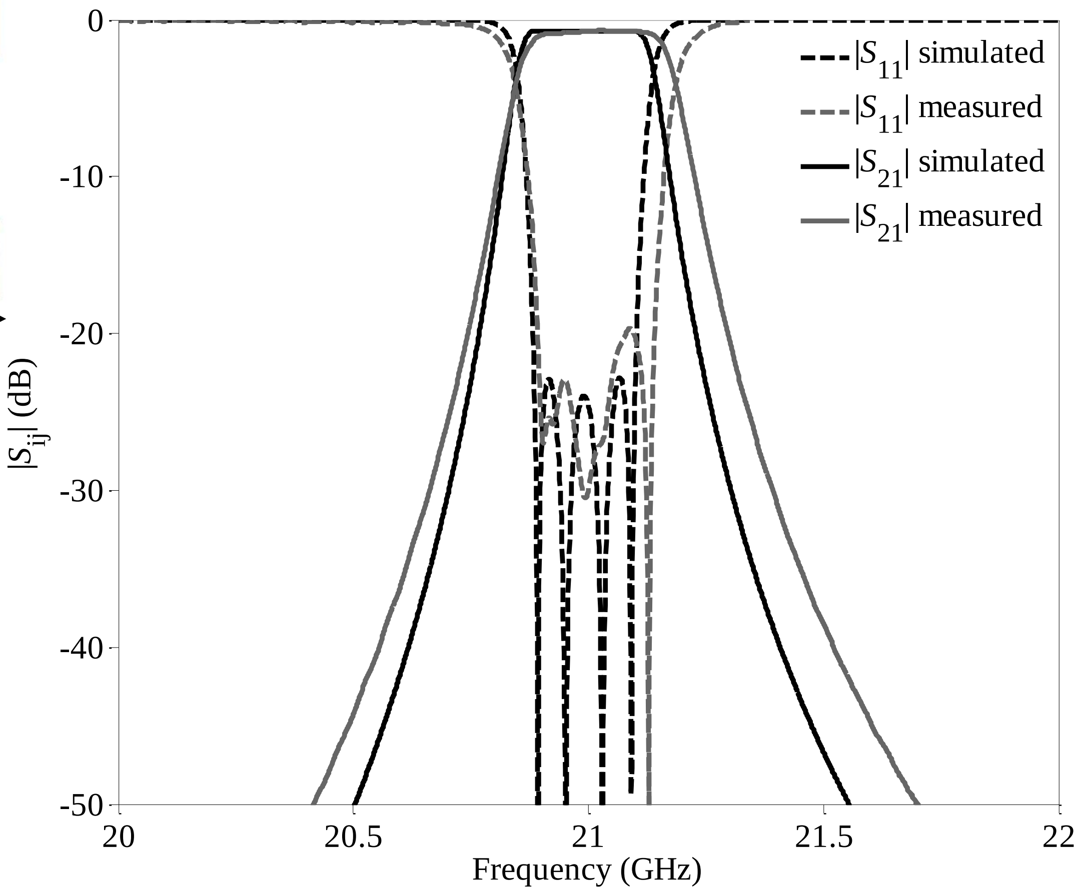


- Air cavity: frequency drift of 29.3 MHz at -40° C
- AFSIW cavity: frequency drift of 0.01 MHz at -40° C

T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

Filter Fabrication and Measurement - Uncompensated





- 4th order AFSIW filter
- 300 MHz BW
- 0.7 dB IL
- 1572 *Q*-factor (h_2 = 50 mils)
- Not thermally compensated

T. Martin, A. Ghiotto, T. Vuong and F. Lotz, “Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

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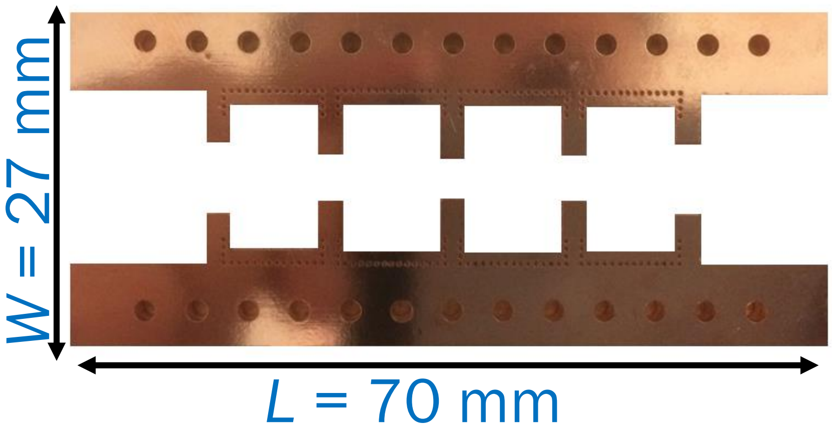
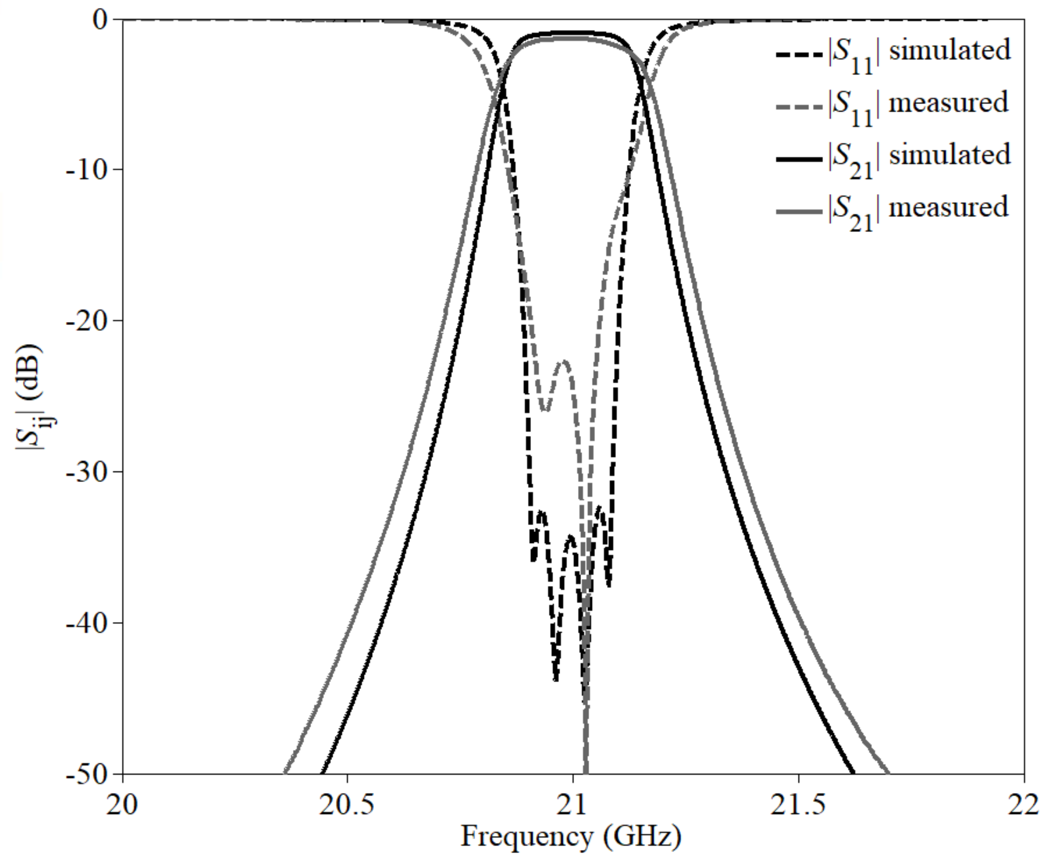
Filter Fabrication and Measurement - Compensated





- 4th order AFSIW filter
- 300 MHz BW
- 1.08 dB IL
- 1031 *Q*-factor (h_2 = 50 mils)
- Thermally compensated

T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

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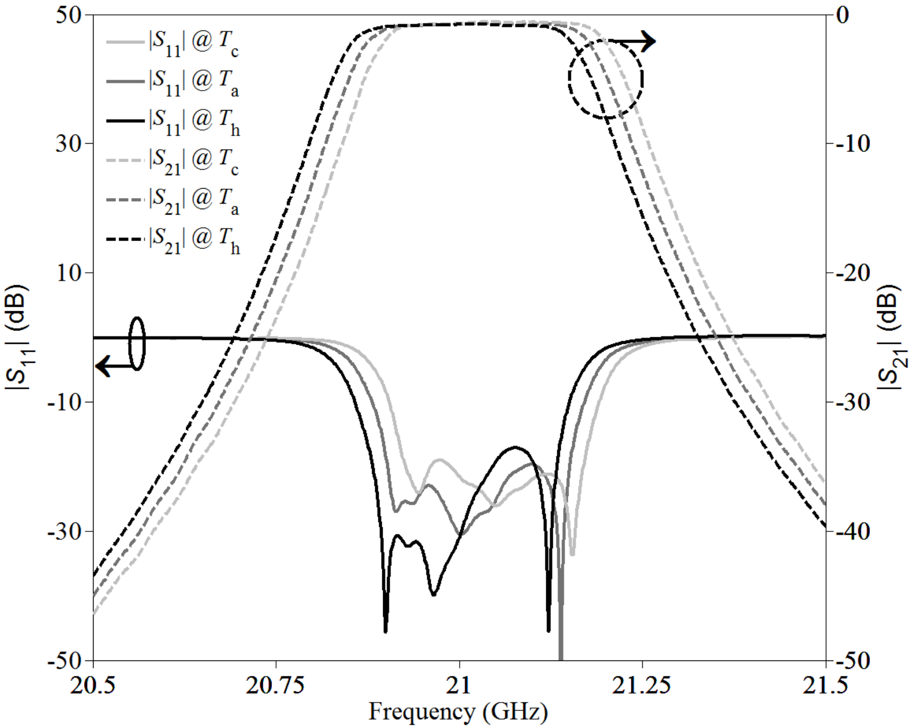
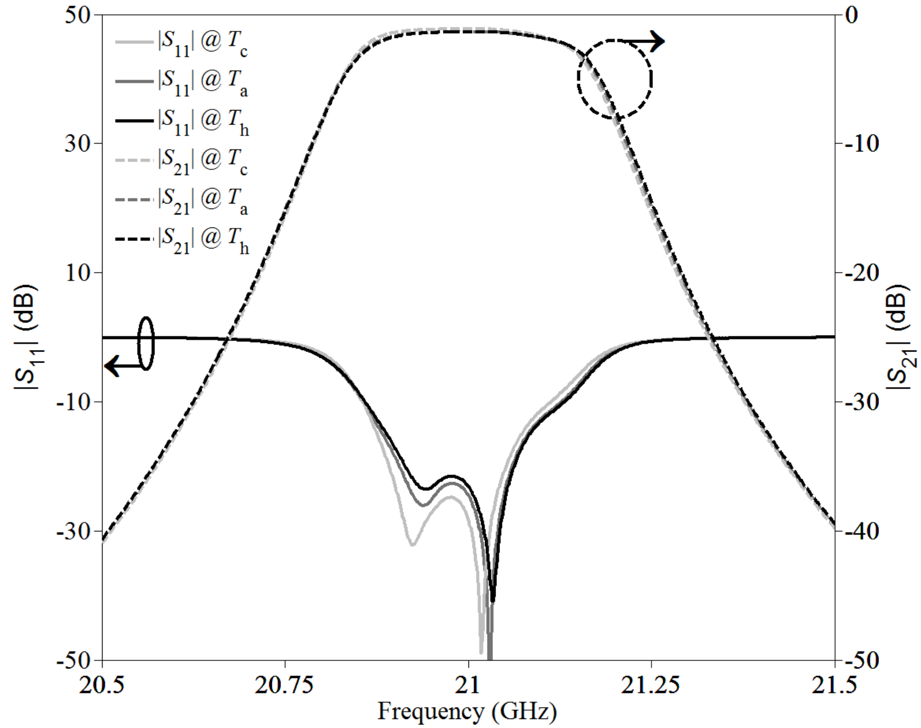
AFSIW Filters Temperature Measurement





- Uncompensated filter: frequency drift of 23 MHz at -40° C
- Compensated filter: frequency drift of -3 MHz at -40° C
- Insertion losses are increased by 30%

T. Martin, A. Ghiotto, T. Vuong and F. Lotz, "Self-temperature-compensated air-filled substrate integrated waveguide cavities and filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3611-3621, Aug. 2018.

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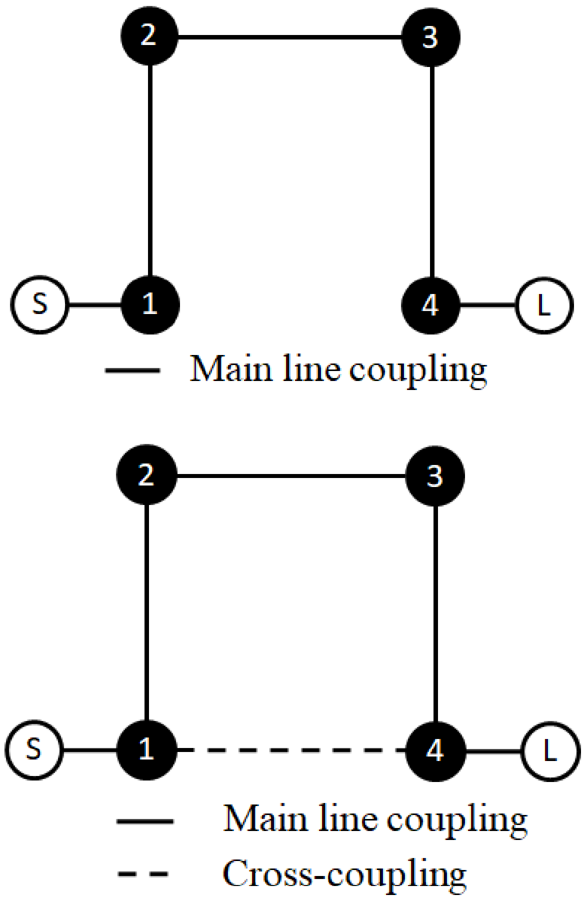
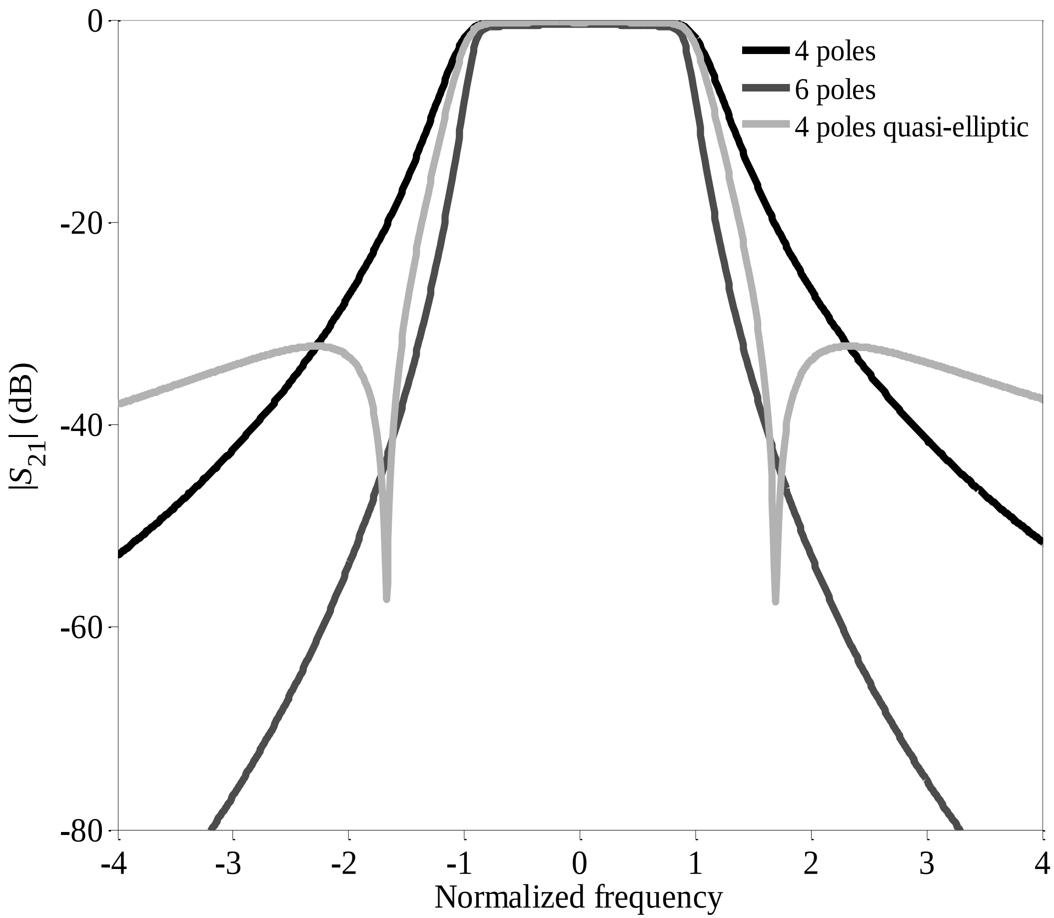
Quasi-Elliptic AFSIW Cross-Coupled Topology





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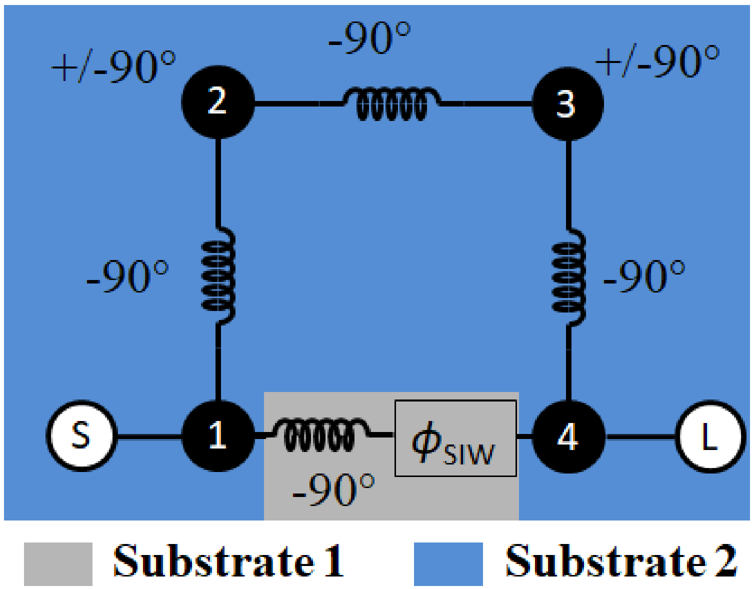
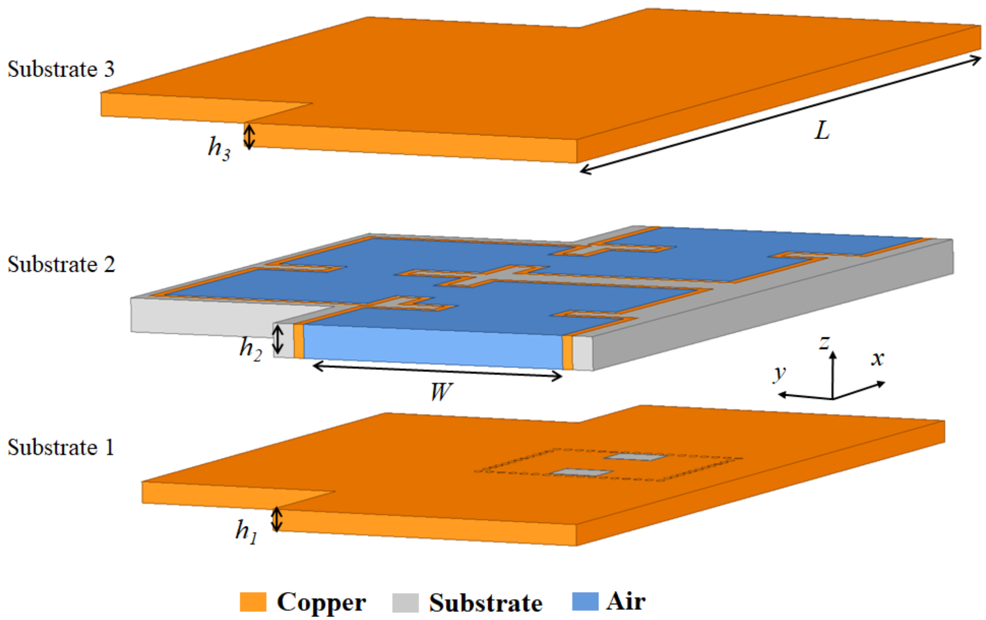
Quasi-Elliptic AFSIW Cross-Coupled Structure



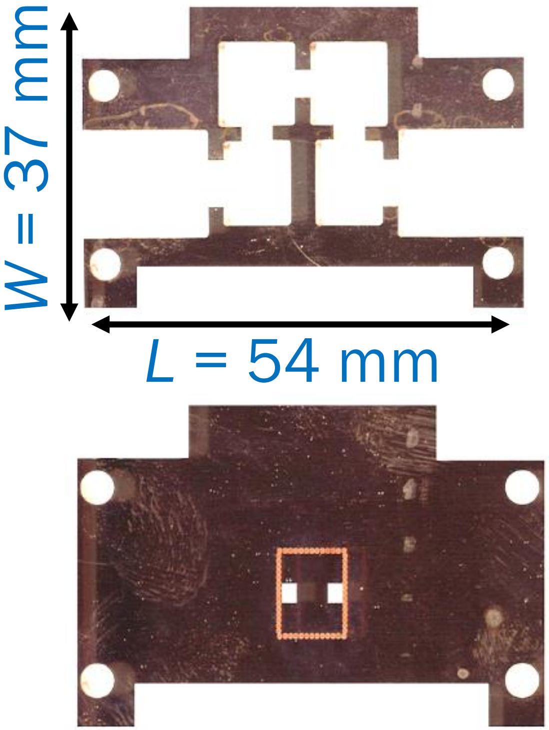


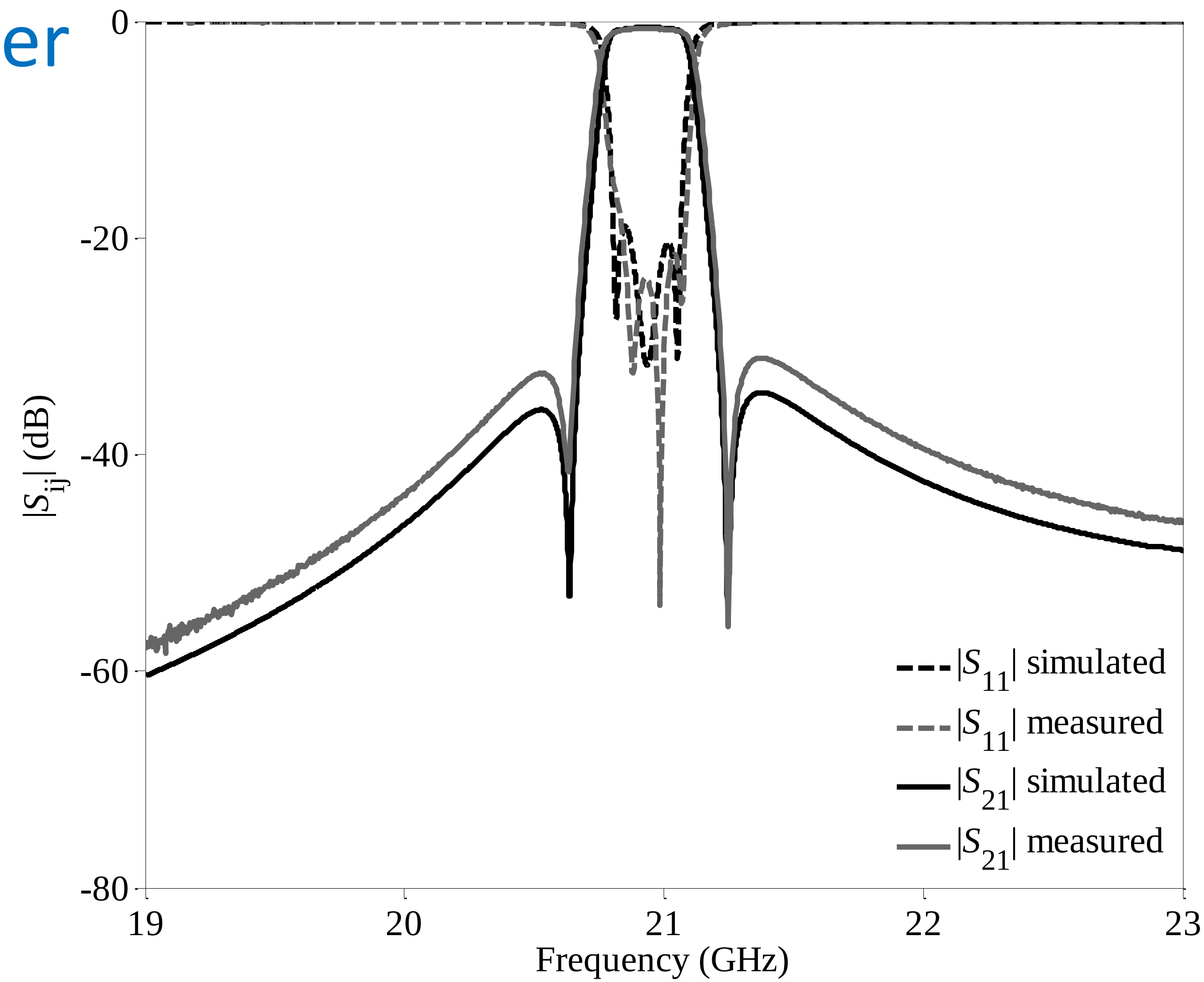
- Primary path implemented in the inner substrate (substrate 2)
- Secondary path implemented in the bottom substrate (substrate 1)
- Cross-coupling implemented through etched inductive iris and SIW transmission line

T. Martin, A. Ghiotto, T. Vuong, K. Wu and F. Lotz, "Compact Quasi-Elliptic and Highly Selective AFSIW Filters with Multilayer Cross-Coupling," 2019 IEEE MTT-S International Microwave Symposium - IMS, Boston, MA, Jun. 2019.

TZs Implementation

Manufactured Filter





- 4^{th} order AFSIW filter
- 0.7 dB IL
- 1478 *Q*-factor (h_2 = 60 mils)

Low-Cost Planar Filter State of the Art

Specifications	[8] IMS 2015	[9] T-MTT 2008	[10] T-MTT 2012	**This work**
Process	PCB	PCB	PCB	**PCB**
Technology	Combline SIW	SIW	SIW	**AFSIW**
PCB substrate material	Rogers TMM4	Rogers 5880	Taconic TLY-5	**Rogers 6002**
Filter order	4th	4th	4th	**4th**
Total height (mm)	3.175	0.508	0.508	**2.54**
Area (mm²)	450	350	100	**1560**
Center frequency (GHz)	5.68	20.5	27	**20.99**
-3 dB bandwidth (%)	1.8	3.41	7.41	**1.71**
Insertion loss (dB)	3.6	0.9	2.1	**0.71**
Rejection frequencies (GHz)	5.56 / 5.8	19.6 / 21.4	25.6 / 28.4	**20.63 / 21.25**
Unloaded *Q*-factor	225	520	116	**1478**

[8] S. Sirci, F. Gentili, J. D. Martínez, V. E. Boria, and R. Sorrentino, “Quasi-elliptic filter based on SIW combline resonators using a coplanar line cross-coupling,” *IEEE MTT-S Int. Microw. Symp.*, Phoenix, AZ, 2015.

[9] X. Chen and K. Wu, “Substrate integrated waveguide cross-coupled filter with negative coupling structure,” *IEEE Trans. Microw. Theory Techn*,. vol. 56, no. 1, pp. 142-149, Jan. 2008..

[10] K. Gong, W. Hong, Y. Zhang, P. Chen, and C. J. You, “Substrate inte-grated waveguide quasi-elliptic filters with controllable electric and magnetic mixed coupling,” *IEEE Trans. Microw. Theory Techn*,, vol. 60, no. 10, pp. 3071-3078, Oct. 2012.

Outline

AFSIW
www.afsiw.com

- Motivation
- The Substrate Integrated Waveguide (SIW) Technology
- The Air-filled SIW (AFSIW) Technological Platform
- Focus on AFSIW Filters for the New Space Applications
  - Full input multiplexer (IMUX) implementation
- Conclusion and Perspective

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Conclusion

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- AFSIW is leveraging SIW performances (Q-factor of up to 1900 has been measured at K-Band (with h_2 = 75 mils) and 1500 at Ka-band (with h_2 = 60 mils))
- Thermal compensation has been demonstrated taking advantage of the dielectric slabs
- Creative implementation of transmissions zeros has been demonsrated using the multilayer aspect
- There is still lot of work to be done playing with the multilayer PCB possibility

Perspective

202X

IP licencing

2021

2019

2012

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

Perspective

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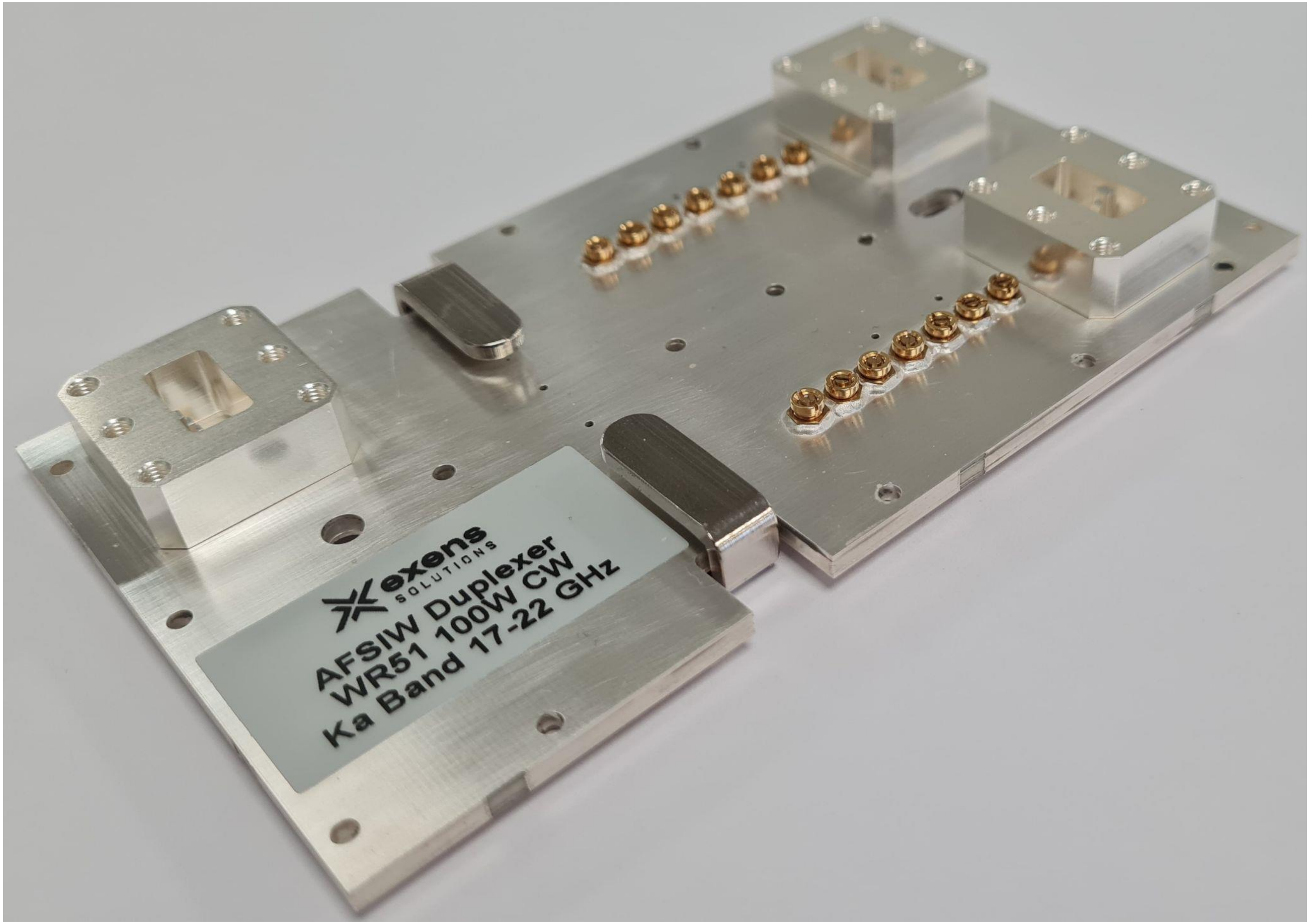

Perspective

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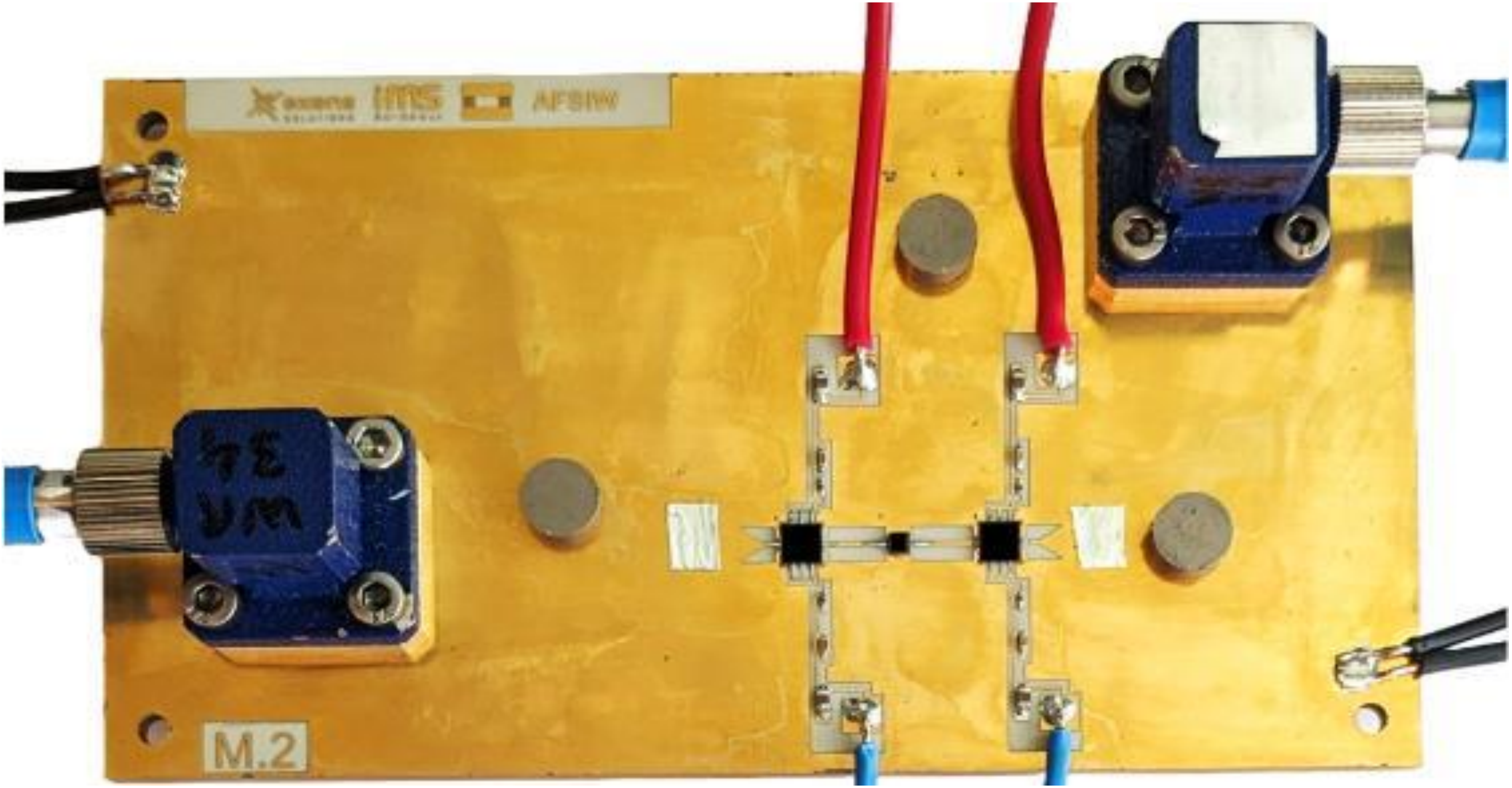

Acknowledgement

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