Photonic Integrated Circuits (PIC) in Space:
Advancing Earth's Atmospheric Sounding Capability

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Outline

- **Why Earth's Atmospheric Sounding?**
- **NASA and NOAA investments on technology**
- **What is PBL?**
- **Technology state of the art**
- **Integrated photonics**
- **The HyMPI project**
  - **Laser multi-tone source**
  - **Electro-optical modulator**
  - **Photonic integrated channelizer**
  - **The first signal received**
- **Conclusions**
- **Acknowledgments**

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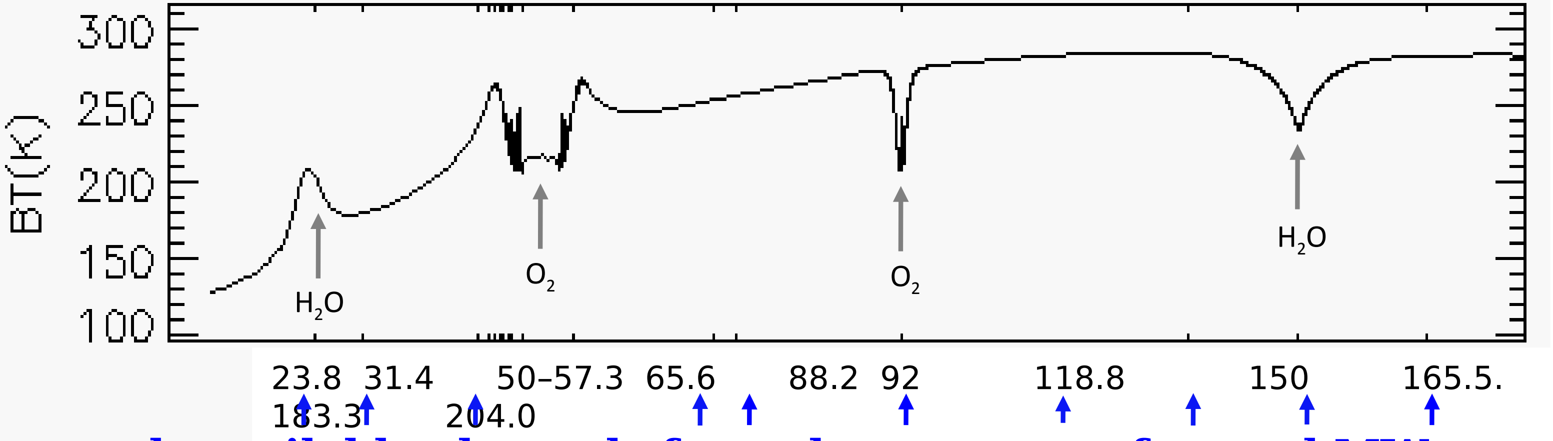
Why Earth's Atmospheric Sounding?

rth's surface emitted Blackbody Radiation, transmitted through the atmosphere and measured from a space-borne microwave sensor



Currently available channels from the program of record MW sensors (GHz)

- **MW sensors from the current and planned programs have a very limited, sparsely sampled set of channels and a large, significant part of the spectrum is entirely missed**
- **Image courtesy Dr. Antonia Gambacorta**

- **Measured microwave (MW) radiation in the thermal region (10 – 250 GHz) is inverted to retrieve information on atmospheric temperature, water vapor and clouds**

These products are used in numerous applications of societal benefit such as numerical weather prediction models, nowcasting of extreme events, climate science.

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NASA and NOAA investments on technology

- **The NASA Planetary Boundary Layer (PBL) Incubation Study Team Report** lists hyperspectral microwave sensors as an "*Essential Component*" of the future global PBL observing system, to provide improved PBL and free tropospheric 3D temperature and water vapor structure context to active measurements (*e.g.*, lidar, radar) and in conjunction with passive sensors (*e.g.*, infrared, RO).

  - **Our team at GSFC has initiated a NASA Earth Science and Technology Office Incubation Instrument Proposal research project titled**: "*Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)*", https://esto.nasa.gov/project-selections-for-iip-21/#Gambacorta

  - **We are also funded through the NASA Decadal Survey Incubation Planetary Boundary Layer project to deploy an airborne campaign to demonstrate an ASIC-based MW hyperspectral technology, titled:** *"Hyperspectral Capability for the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR): Enhancing Capability for Future PBL Suborbital Campaigns and Enabling PBL Science from Space ,* https://esto.nasa.gov/project-selections-for-dsi-21/#Kroodsma

- **Hyperspectral Microwave Measurements** have been long advocated by meteorological and space agencies worldwide to improve temperature, water vapor and hydrometeors retrievals from space (Lipton, 2003; Bauer, 2007; Lambrigsten, 2010; Blackwell, 2010; Boukabara, 2011; Mahfouf, 2015; Aires, 2015; Aires, 2019).

  - **Our team at GSFC has initiated a NOAA funded project**, *"Developing the NOAA Next Generation Hyperspectral Microwave Sensor (HyMS): Instrument Concept and Demonstration of Benefits for the NOAA Mission"*

Slide courtesy Dr. Antonia Gambacorta

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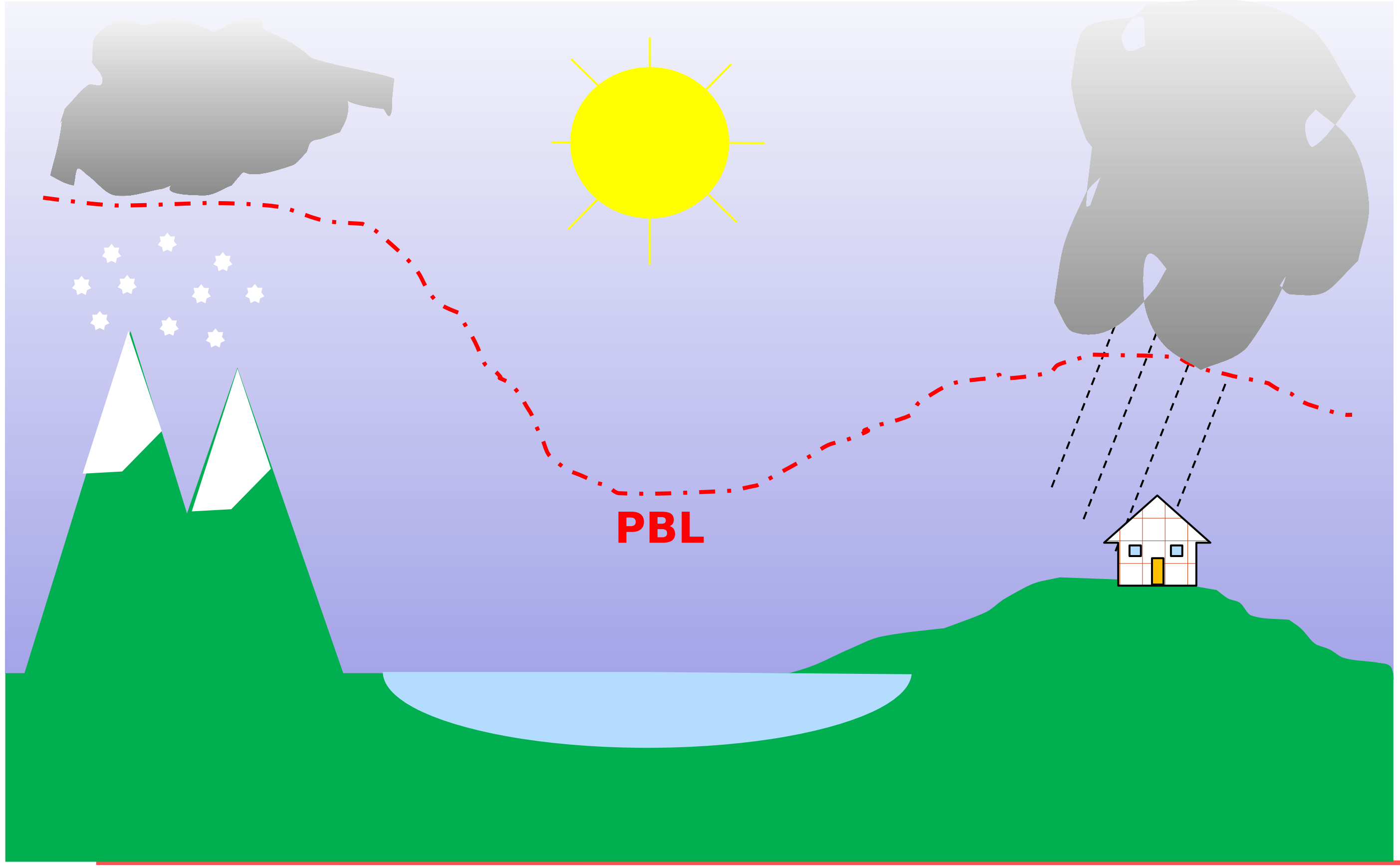
What is PBL?

- PBL is the lowest part of the atmosphere (our "house") and it is where the atmosphere interacts with Earth's surface (oceans, land, ice…). It is where we experience the wheatear and climate.



- Due to technological limitations, there is a lack of global PBL observation
  - Satellites capabilities are limited (low number of channels, high size, weight, power consumption and cost, SWaP-C)
  - The gases from atmosphere impair the measurements from space
  - It is difficult to have information over oceans and other remote locations (i.e.: polar regions), due to limited number of ground-based

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Technology: state of the art

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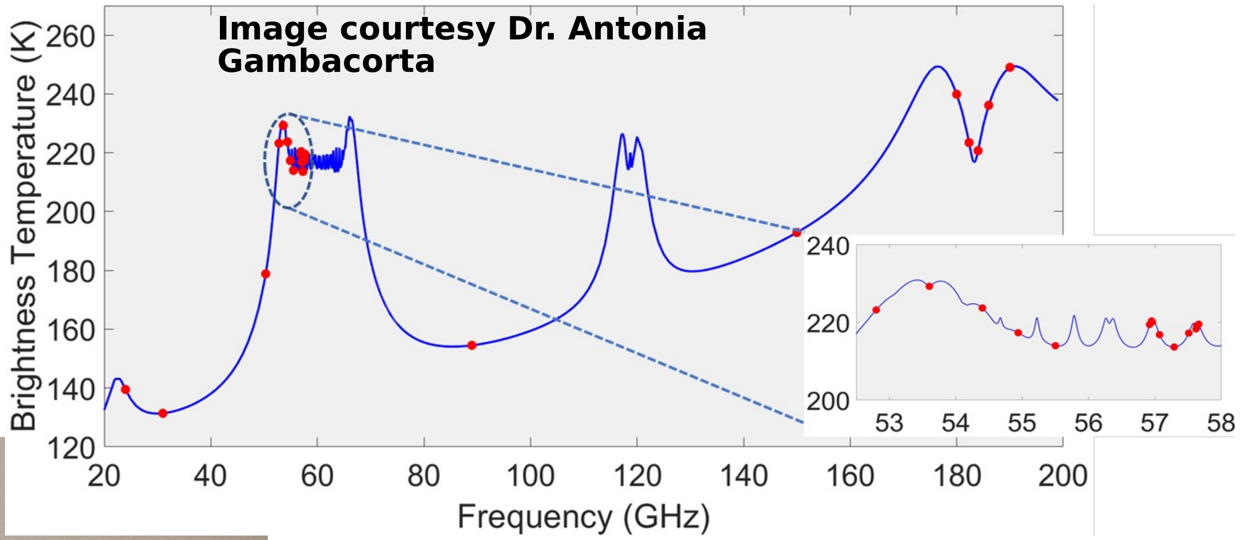
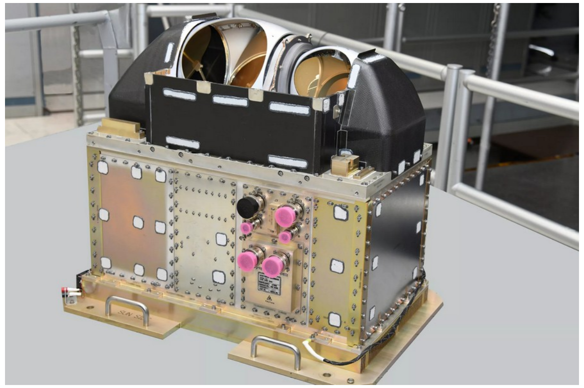
Radio-frequency systems do not meet science requirements.

- **Large number of components**
- **High power consumption**
- **Larger size & weight**
- **Limited bandwidth for components**

Dozen sparsely sampled channels:

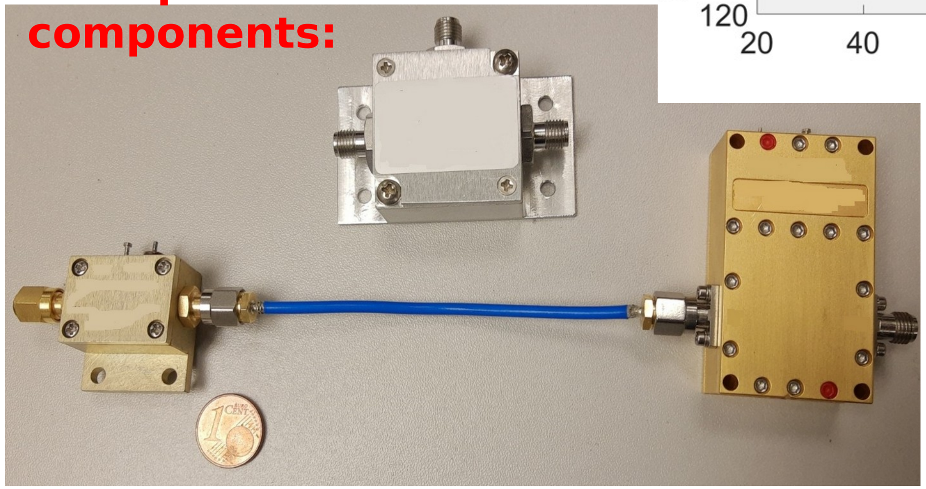




www.nesdis.noaa.gov

Advanced technology Microwave Sounder (ATMS)

Example of RF components:



The technology limitation

- **Low resolution**
- **Lots of information lost**
- **Hard to tune**
- **Low level of redundancy**

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Integrated photonics

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- **We need to <u>break the technological stall </u>to access to an enormous amount of hidden information in the Earth's atmosphere**
- **<u>Integrated photonics</u>: emerging branch of photonics in which waveguides and devices are fabricated as an integrated structure onto the surface of a flat substrate**
- **<u>Properties of photonic integrated</u>**
  - **Ultra compact devices (low size/we**
  - **Low power consumption**
  - **Process ultra-high bandwidth**
  - **Tunable channels**
  - **Reduced cost with integration**
  - **CMOS compatible**

RF vs PIC dimensions:

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Integrated photonics

- **PIC fabrication process is based on existing state-of-the-art electronic integrated circuits (EIC) CMOS foundries tools (deposition, lithography, etching,…)**
- **There are key differences between PIC and EIC**

Feature	PIC	EIC
Signal particle carrier	Photons	Electrons
Building blocks	Active/passive (depends on platform): lasers, amplifiers, modulators, photodetectors, ….	Transistors, capacitors, resistors, …
Substrate	Several (depends on applications) – hybrid integration available	Metal-oxide (CMOS technology)

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Integrated photonics

- **Examples of platform for PIC:**

Substrate	Properties	Advantages	Devices
Glasses	Low price / Rare Earth incorporation	Low loss / Easy to fabricate	Passive, Amplifiers
SiO_xN_y:SiO_2:Si TiO_2/SiO_2/Si	Cheap and versatile fabrication	CMOS compatible	Passive
Lithium Niobate	Electro-optic, Acusto-optic, Non-linear, Bi-rifrangent	Easy control of light Anisotropic	Passive
III-V compounds (InP, GaAs)	Electro-optic light source, detection	High level of integration	Passive, Amplifiers / Lasers
Polymers	Electro-optic/Thermo optic/Non-linear	Versatility and wide range of physical properties	Chemical and biological sensors, EO modulators,

- **Results:**
  - **Minimized cost and power consumption**
  - **Improved scalability ⇒ higher number of channels**
  - **Improved redundancy of the system ⇒ longer missions**
  - **Multiple functionalities ⇒ multiple missions/targets**

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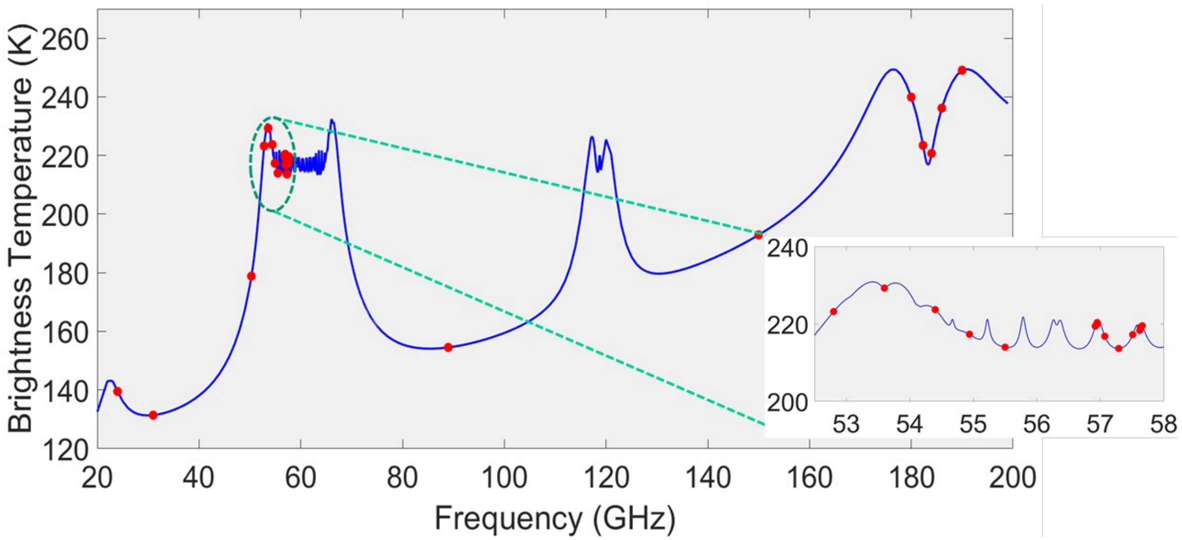
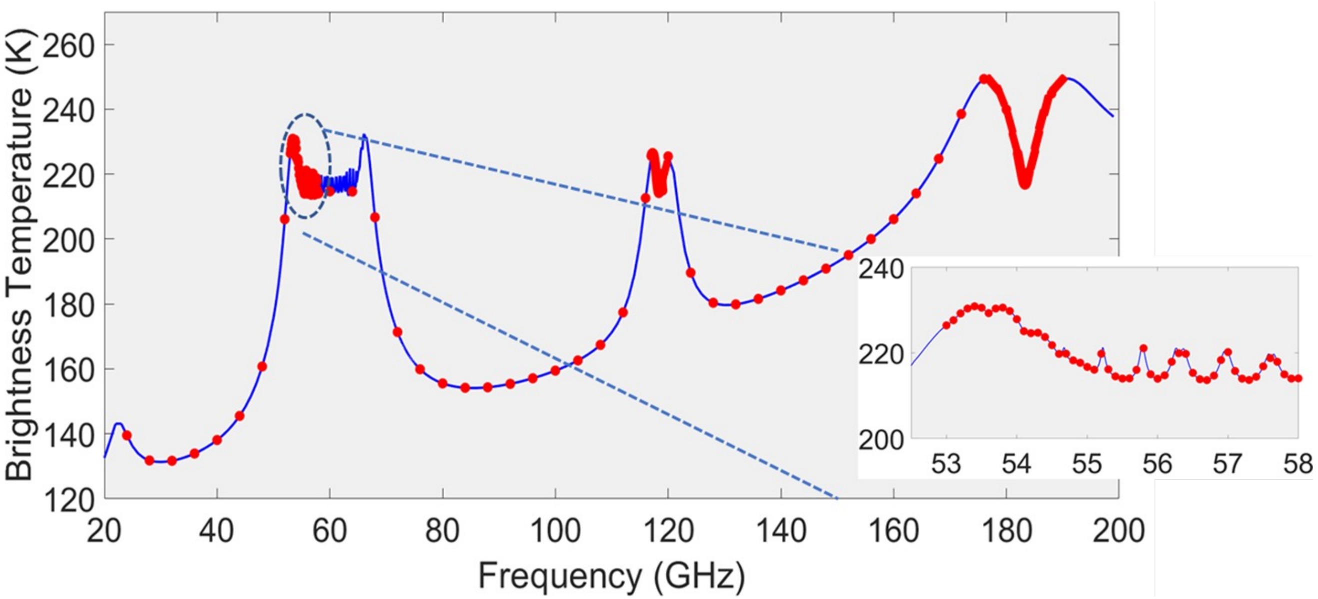
What PIC can do?





- **ATMS:**
  - **~20 sparse channels (not contiguous spectrum)**
  - **Missing critical information**
  - **>> 2-U cubesat footprint**

- **PIC enabled hyperspectral MW technology:**
  - **Contiguous spectrum coverage**
  - **Hyperspectral resolution: 10 MHz (or lower!) with support of ASIC**
  - **1U / 2-U cubesat footprint**

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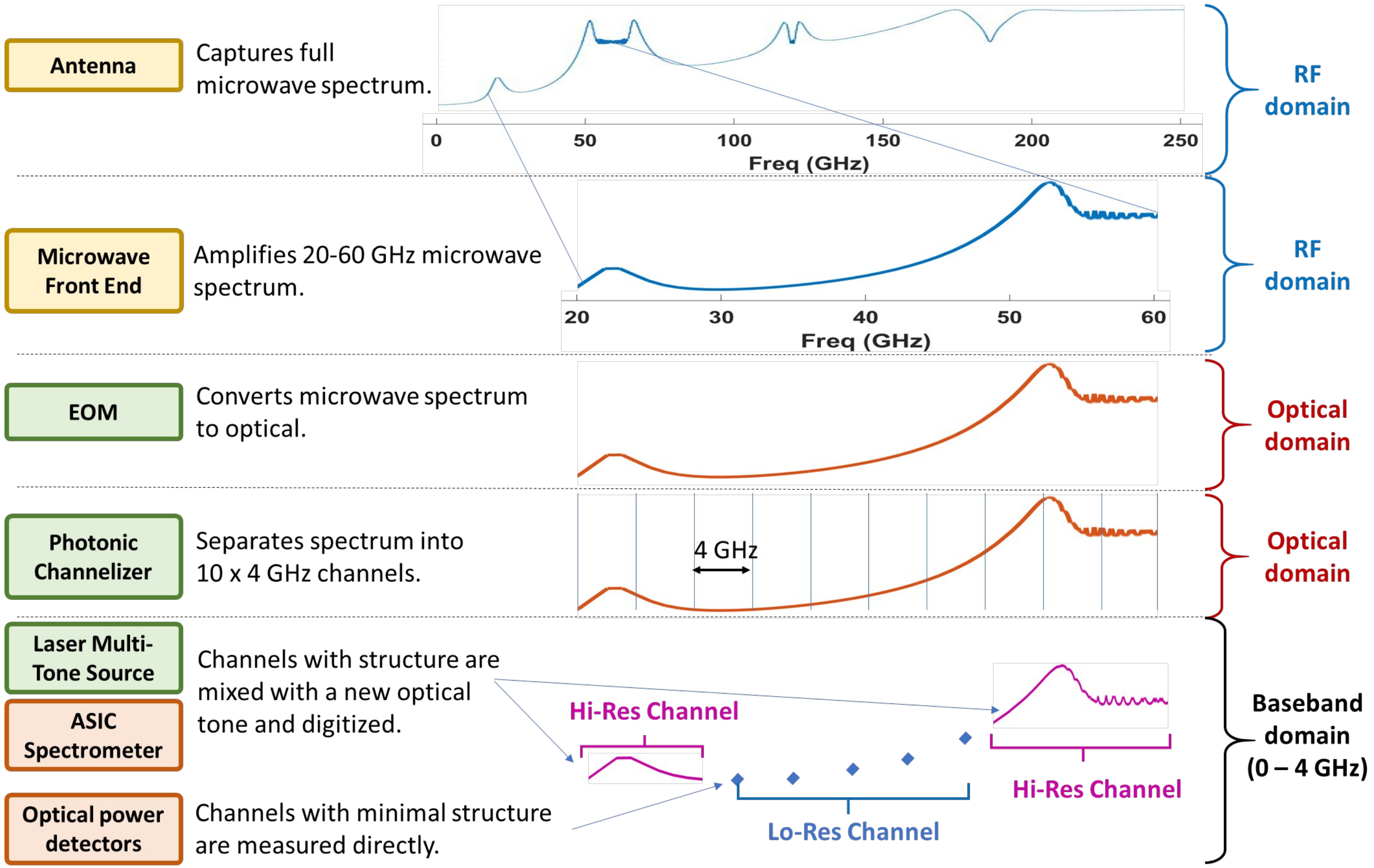
The HyMPI concept



- HyMPI uses different PICs developed in different platforms
- This allows to exploit the technological benefits provided by different platforms
- The **goal**: provide a broadband and hyperspectral (thousands of channels) instrument with limited SWaP-C (for cubesat) for PBL measurements

RF – radio frequency; EOM – electro-optic modulator; ASIC – application specific integrated circuit;

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Preliminary Observations and Simulations Sensitivity Experiments(OSSEs)

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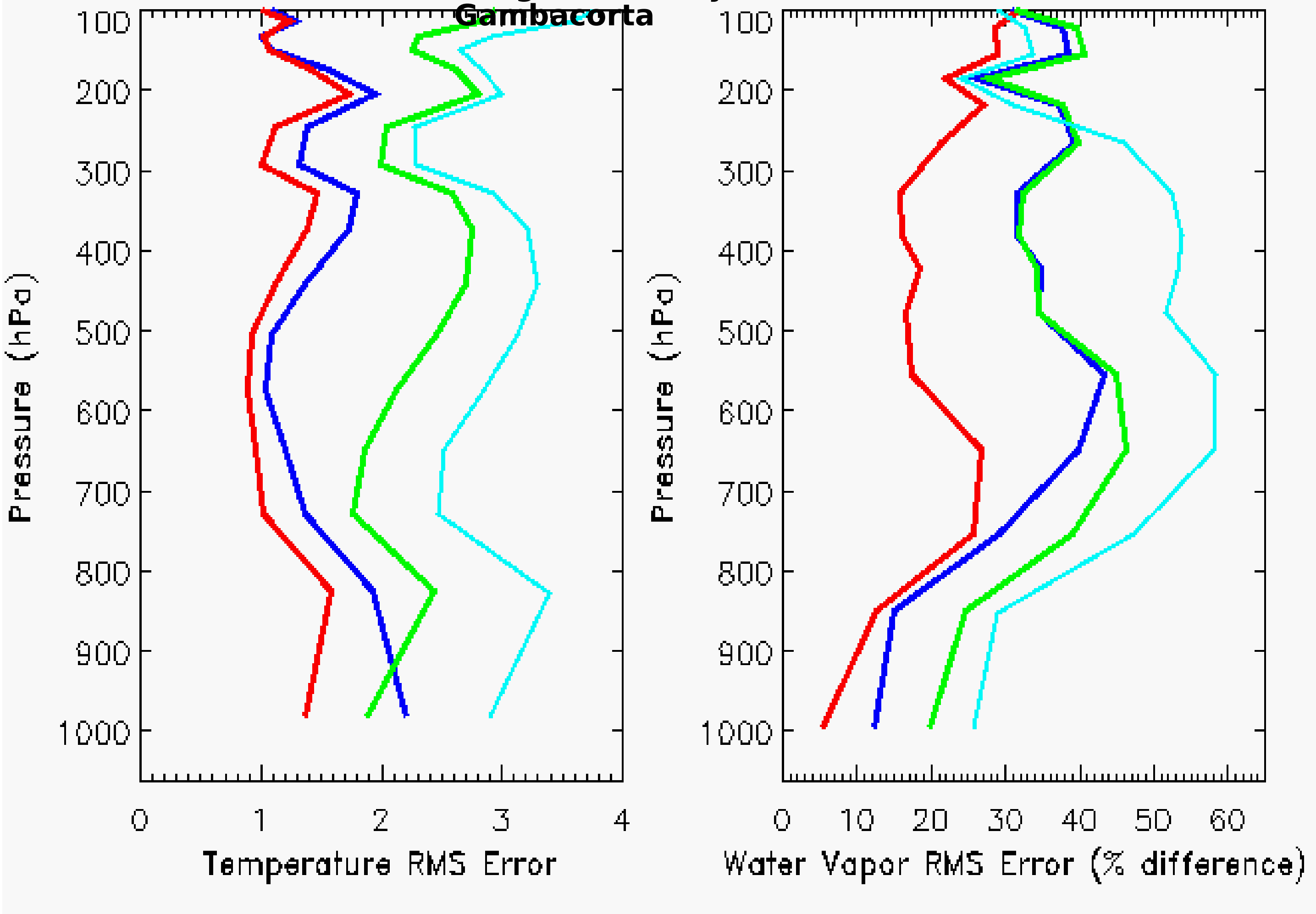
Images courtesy Dr. Antonia Gambacorta



- HyMPI (red) reduces ATMS (blue) temperature Root Mean Square (RMS) error (left) by 50% in the PBL and 20% in the mid/upper troposphere.
- Water vapor RMS error (right) improves by ~50% in the PBL and along the full extent of the mid/upper troposphere.
- Both improvements, in the PBL and the free troposphere, will potentially enhance the identification of the PBL height.
- Thanks to Antonia Gambacorta, NASA GSFC, for the slide
  - Green curve = a sub-selection of HyMPI’s spectrum, using 118 Ghz and 183 GHz hyperspectral lines only. Cyan = Retrieval first guess.

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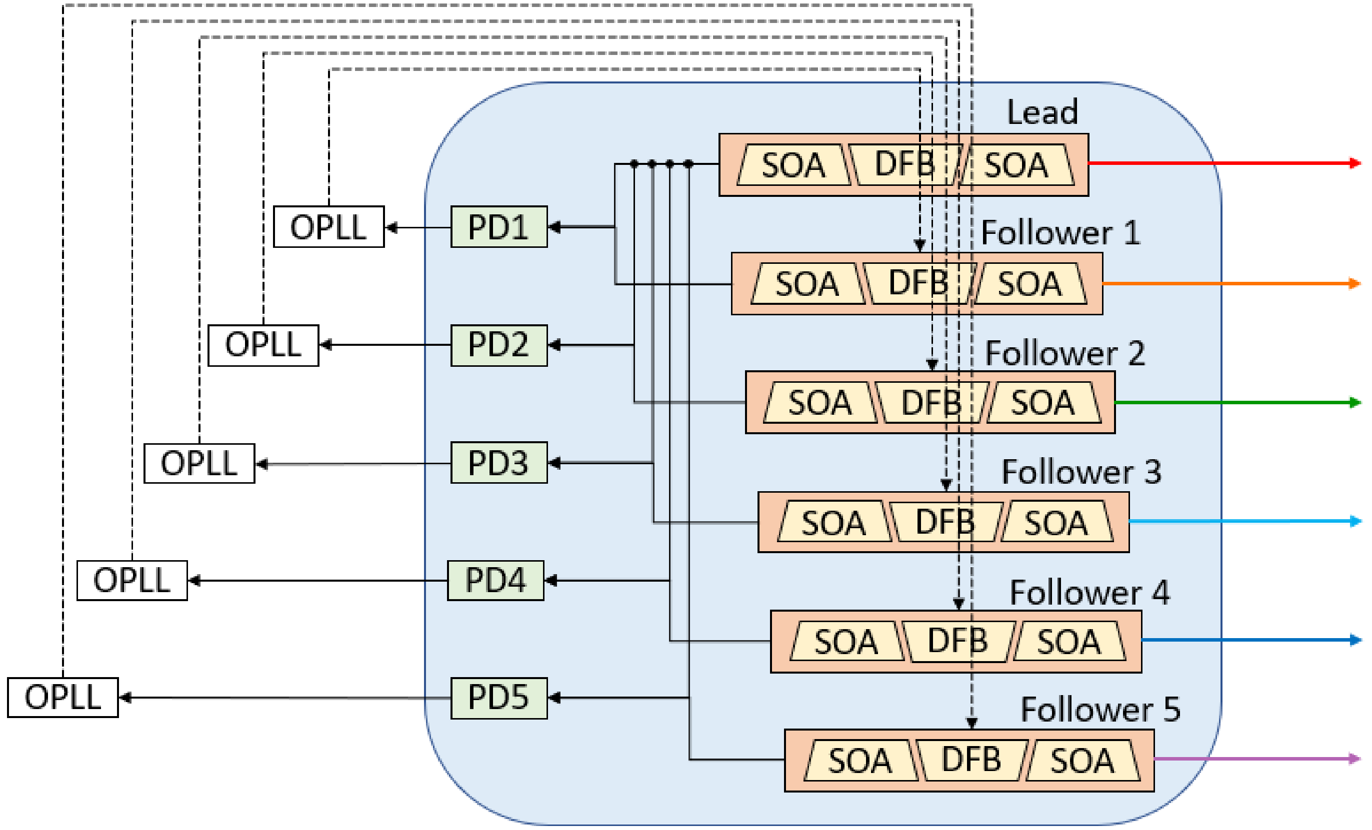
Laser Multi-Tone Source



- **Goal: generates 6 optical carriers locked to the lead lasers**
- **Challenge: locking several lasers and provide at the same time a high stability and low frequency drift**
- **The device is under development by Freedom Photonics LLC**

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Electro-optical phase modulator

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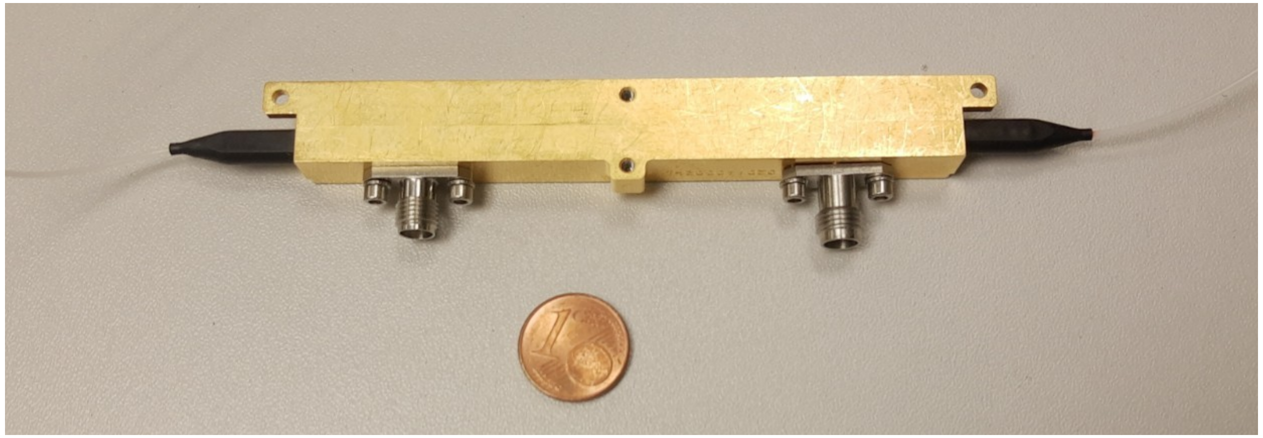
- **We are considering different products (COTS parts) and technologies (PICs)**



- **Goal: modulation > 40 GHz with high electro-optical modulation efficiency**
- **Lithium niobate and thin-film lithium niobate technologies can provide ultra-fast, efficient and compact solutions**
- **Both COTS and PICs parts are considered for this subsystem**

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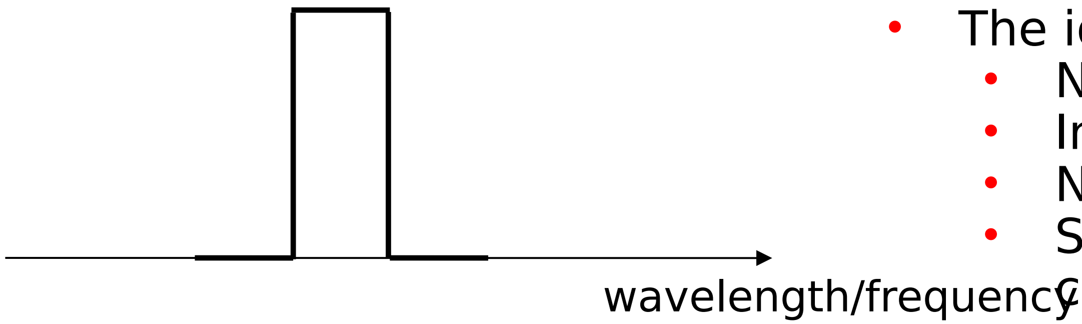
Photonic Integrated Channelizer

- **Goal:**
  - **Tunable multi-channel 4 GHz bandwidth/channel separation**
  - **Compact optical filter with high noise rejection**
  - **Flat-top response**
  - **Limited power consumption**

- **Challenge: Manufacturing/technological limitations strongly impact the filtering response**
  - **The filter shape becomes more and more sensitive to fabrication inaccuracies as the performance of the filter increase**
  - **This can lead to spectral distortions or signal to noise ratio degradation (and this can have a severe impact on the spectrum analysis)**



- The ideal channelizer is the rectangular filter:
  - No distortion (flat-top response)
  - Infinite rejection
  - No loss
  - Small, light and passive (no power consumption)

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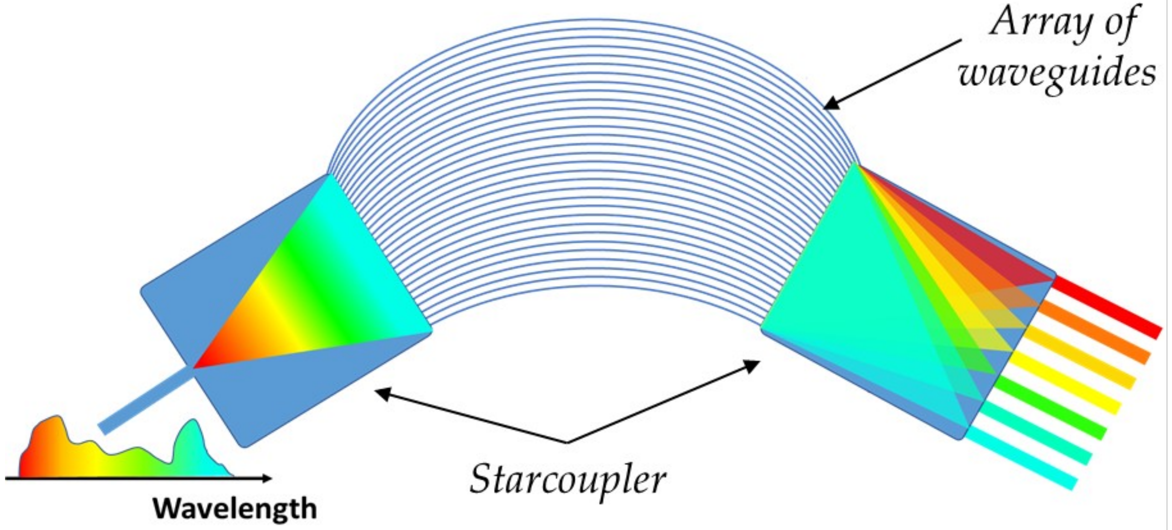
Photonic Integrated Channalizer

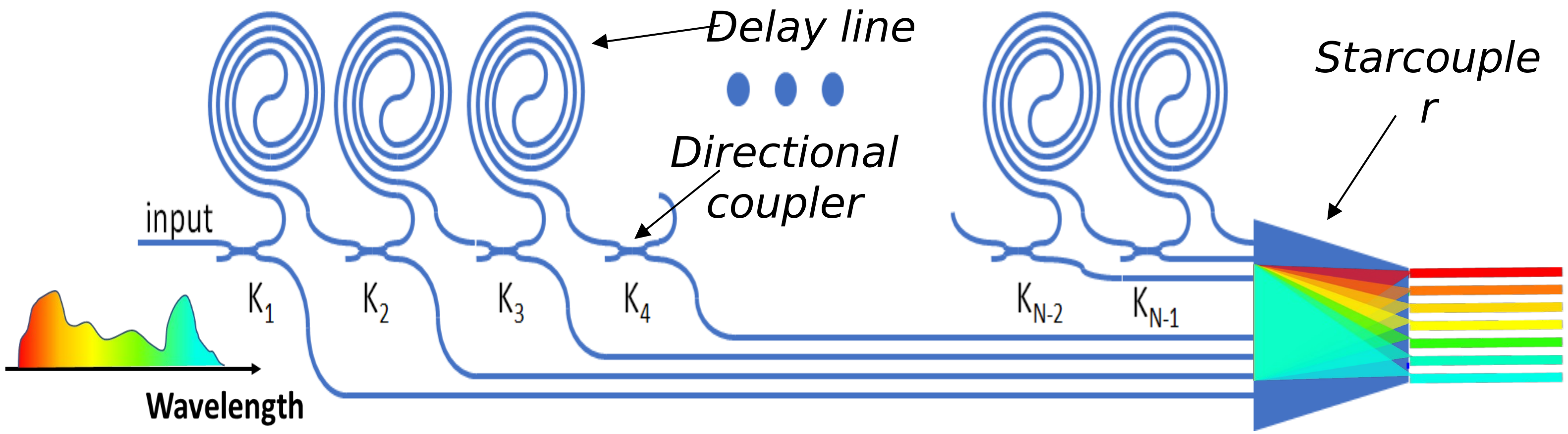
- **Arrayed waveguide grating (AWG) are common planar devices used as multiplexers/demultiplexers in wavelength division multiplexing (WDM) systems**
  - **However, these devices show limited spectral performance since the spectral resolution depends on the interference order of the grating (number, group index and length of the waveguides in the array)**

Classical approach: Parallel AWG (PAWG):



Photonic Integrated Channalizer

- **Our proposed device is composed of one delay lines and N directional couplers (DC) that siphons-off fractions of the input signal.**
- **The spectral filter shape response is the Fourier transform of the intensity distribution (due to the DCs' configurations) at the input of the starcoupler (SC)**
  - **The SC performs the Fourier transform of the input distribution**



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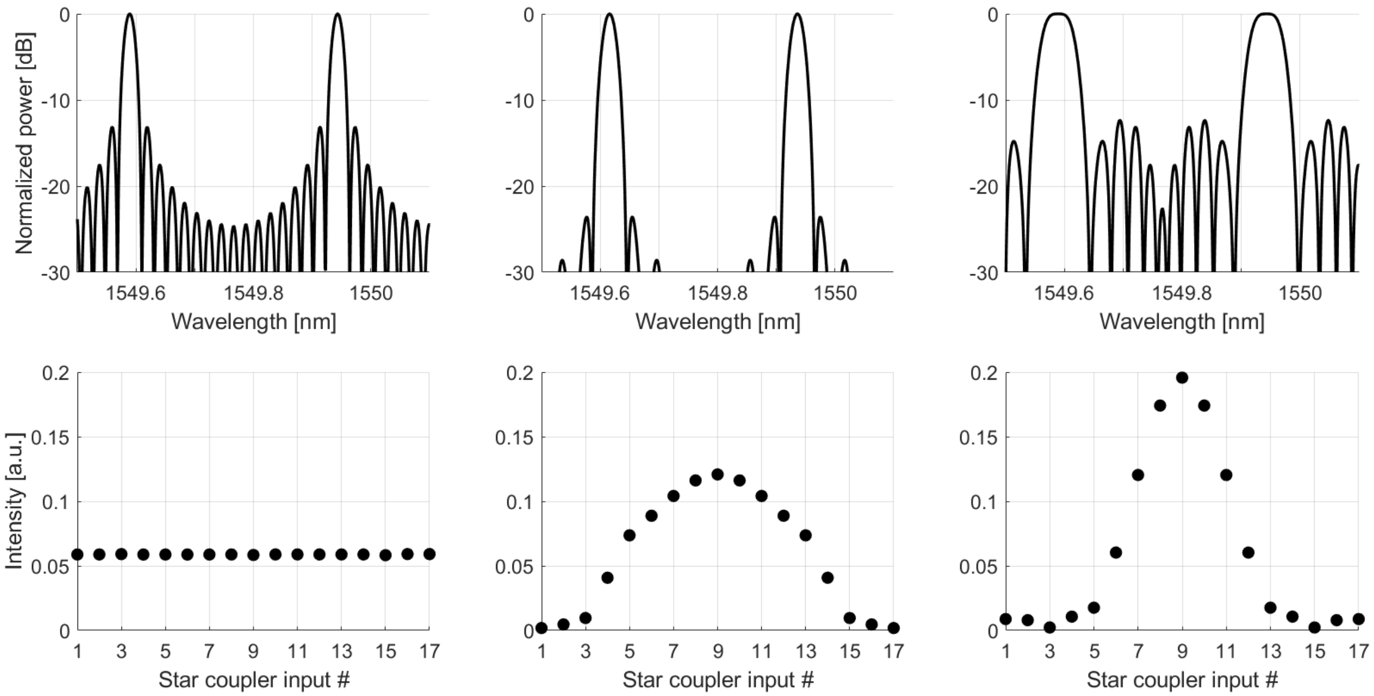
Photonic Integrated Channalizer

- **The innovative design enables the access to:**
  - **The phase delays in each waveguide in the array. This allow the compensation of the fabrication inaccuracies that detriment the performance of the filter**
  - **The DC's splitting ratios. This provides different filter shape and can produce a high-rejection flat-top response (impossible in the PAWG configuration)**



Examples of three different spectral response of the filter

Examples of three different intensity distribution at the star coupler input

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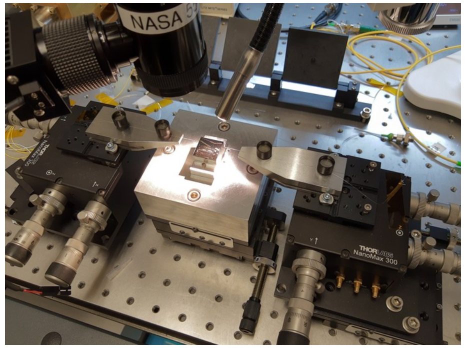
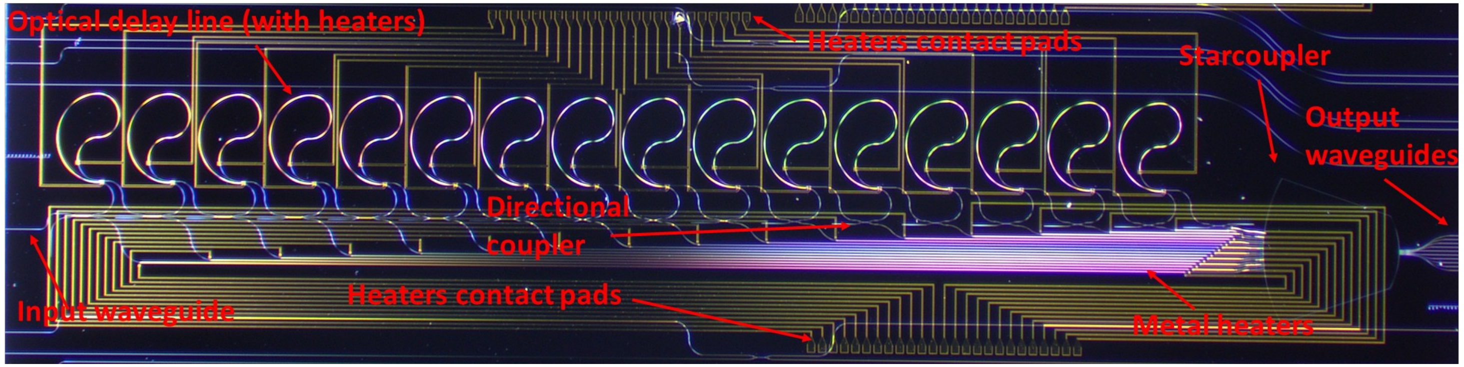
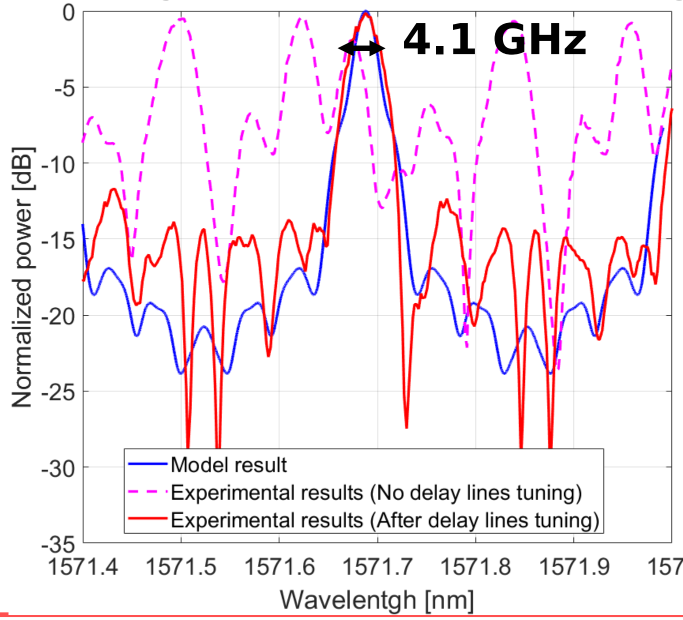
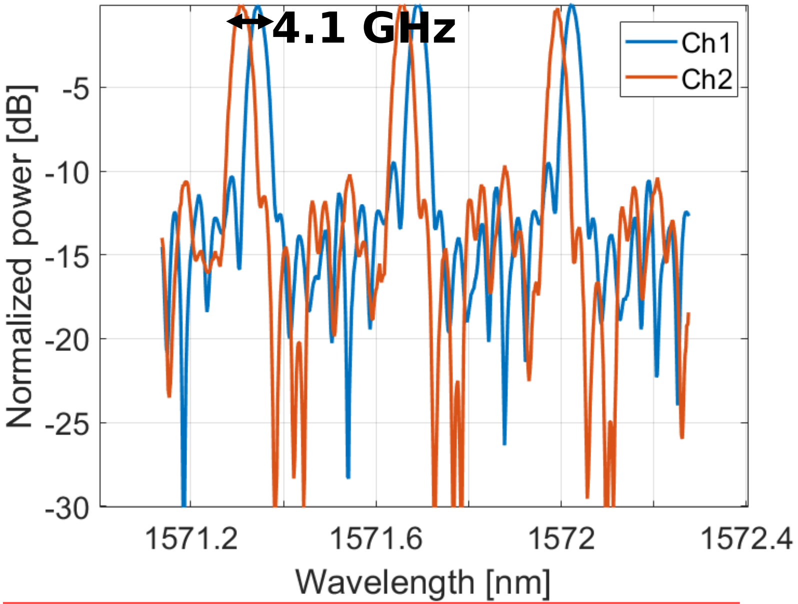
Photonic Integrated Channalizer





F. Gambini, *et al.*, "An Innovative Photonic Integrated Channelizer Design for Hyperspectral Microwave Sounding," in *OSA Optical Sensors and Sensing Congress*, paper HF4E.5.





- **The Gen. 2 device footprint is about 20 mm x 4 mm (SiN platform)**
- **The device has been demonstrated to operate at 4.1 GHz bandwidth/channel separation with about 15 dB of channel rejection**
- ***Patent pending application: Inventor, Dr. M. Stephen (NASA GSFC) - Co-inventors: Dr. R. Moreira (ULL Tech.) and Dr. F. Gambini (UMBC/CRESST II/ NASA GSFC)***

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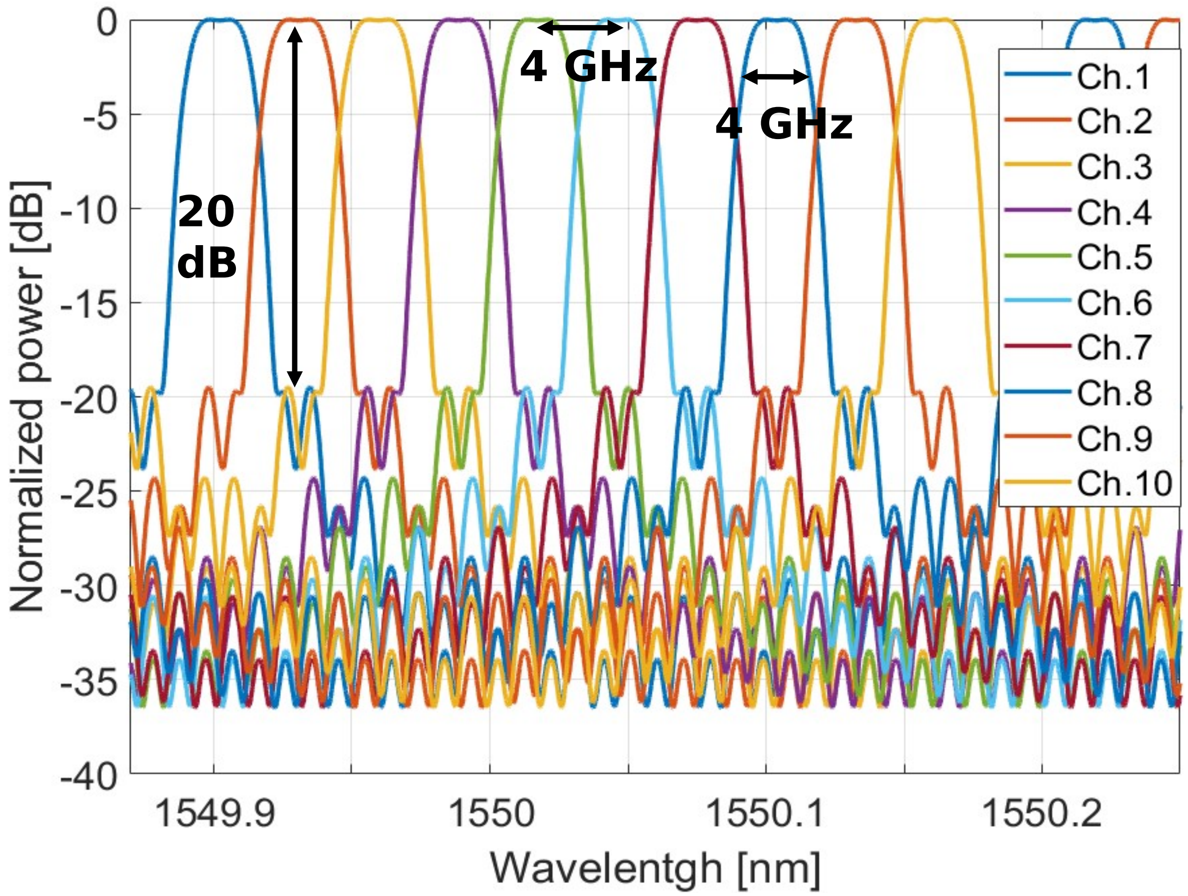
Photonic Integrated Channalizer

- **The next generation of device is currently under fabrication:**



Goals:

- Flat filter response
- Channel separation: 4.0 GHz
- Channel bandwidth: 4.0 GHz
- Filter rejection 20 dB
- Tunable DCs
- Improved power consumption

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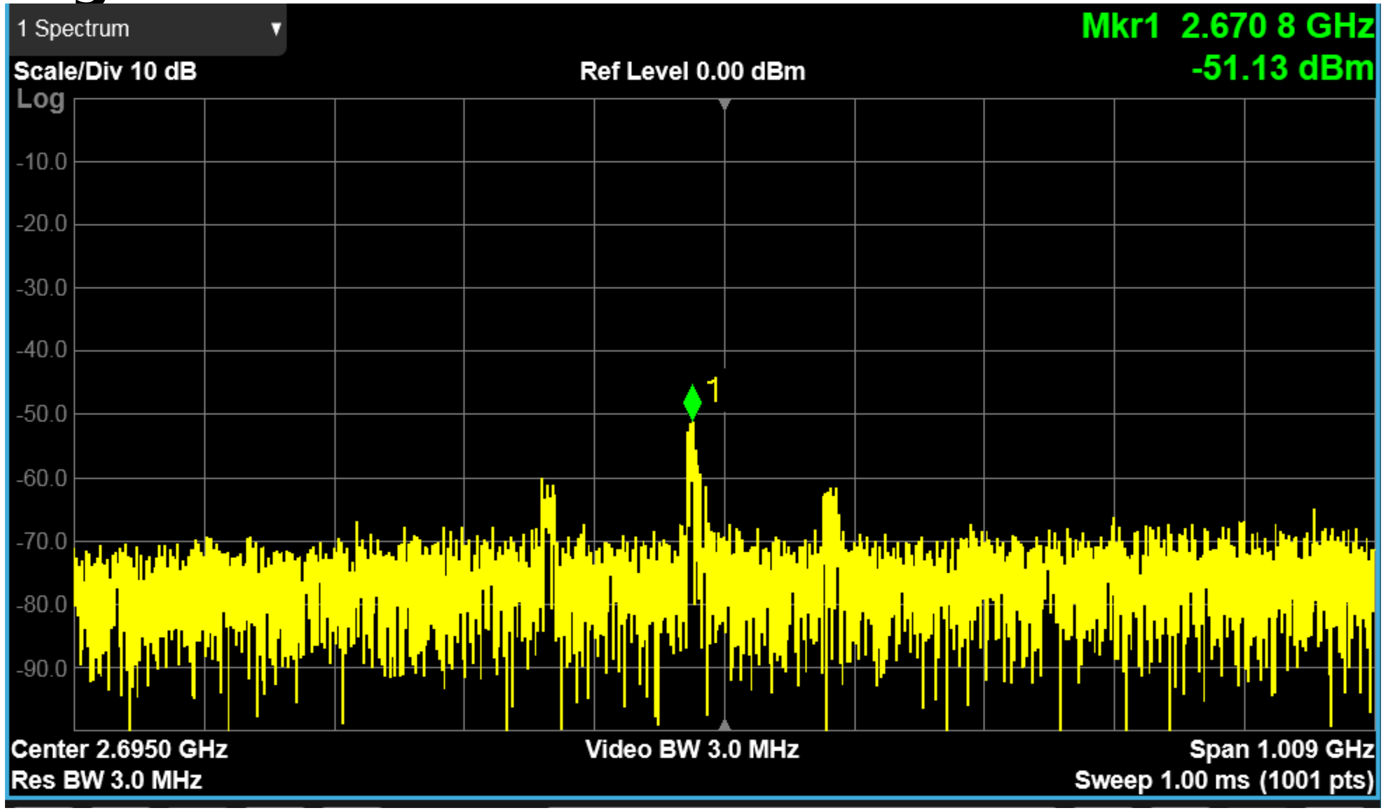
First received signal

- **HyMPI system test started last month (after 8 months from the beginning of the program)… This is our first received signal!**



- 150 MHz modulated carrier (slow but very exciting)
- Two channels locked laser system at 2.67 GHz
- **PICs involved in the experiment**

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Conclusions

- **PICs are a reliable solution to overcome the limitation of the current RF technology**
- **Different photonic integrated platforms are used to fully exploit the advantages of the technology**
- **HyMPI is expected to revolutionize the microwave sounding capabilities, enabling an unprecedented resolution and contiguous spectral coverage for PBL**
  - **At the same time, the system will minimize the SWaP-C**
- **HyMPI will open a new era of advanced atmospheric measurements from space, and it is expected to provide breakthrough improvements in their scientific applications.**

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Thank you!

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