Photonic Integrated Circuits: A Breakthrough Technology for Future Hyperspectral Ultra-Wideband Planetary Boundary Layer Sounders

Fabrizio Gambini[1,2] and Mark Stephen[2]

[1] University of Maryland Baltimore County (UMBC) / CRESST II
[2] NASA Goddard Space Flight Center (GSFC)

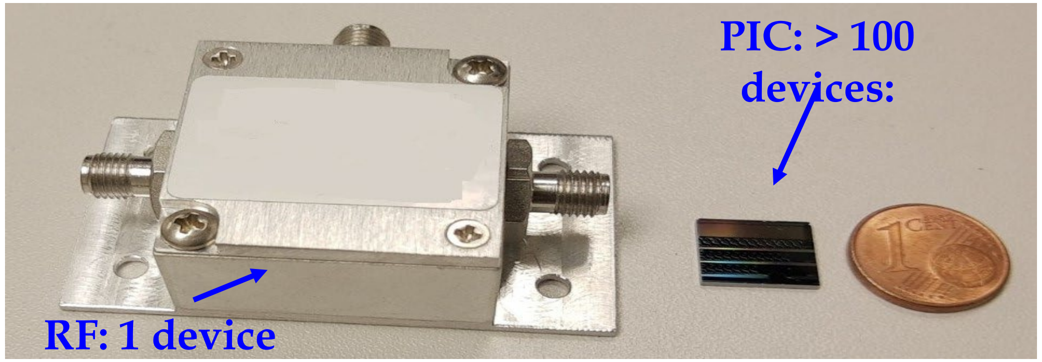
What is integrated photonics?

- **Integrated photonics: emerging branch of photonics in which nano- and micro-meter scale devices are fabricated as an integrated structure onto the surface of a flat substrate**

- **Properties of photonic integrated circuits (PIC):**
  - Ultra compact devices (low size/weight)
  - Low power consumption
  - Process ultra-high bandwidth
  - Tunable channels
  - Reduced cost with integration
  - CMOS compatible

- **Radio-frequency (RF) components limitations:**
  - Large number of components
  - High power consumption
  - Larger size & weight
  - Limited bandwidth for components

RF vs PIC dimensions:



- **Results:**
  - Cheaper and more energy efficient instruments
  - Improved scalability ➔ higher number components/systems on the same substrate
  - Improved redundancy of the system ➔ longer missions
  - Multiple functionalities ➔ multiple scientific missions/targets

What is integrated photonics?

- **PICs are CMOS-compatible: the 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, I/φ modulators, photodetectors, filters, splitters, gratings, phase shifters, switches, couplers, …	Transistors, capacitors, resistors, diodes, inductors
Platforms	Several (application specific), Hybrid integration between different platform available	Metal-oxide (CMOS technology)

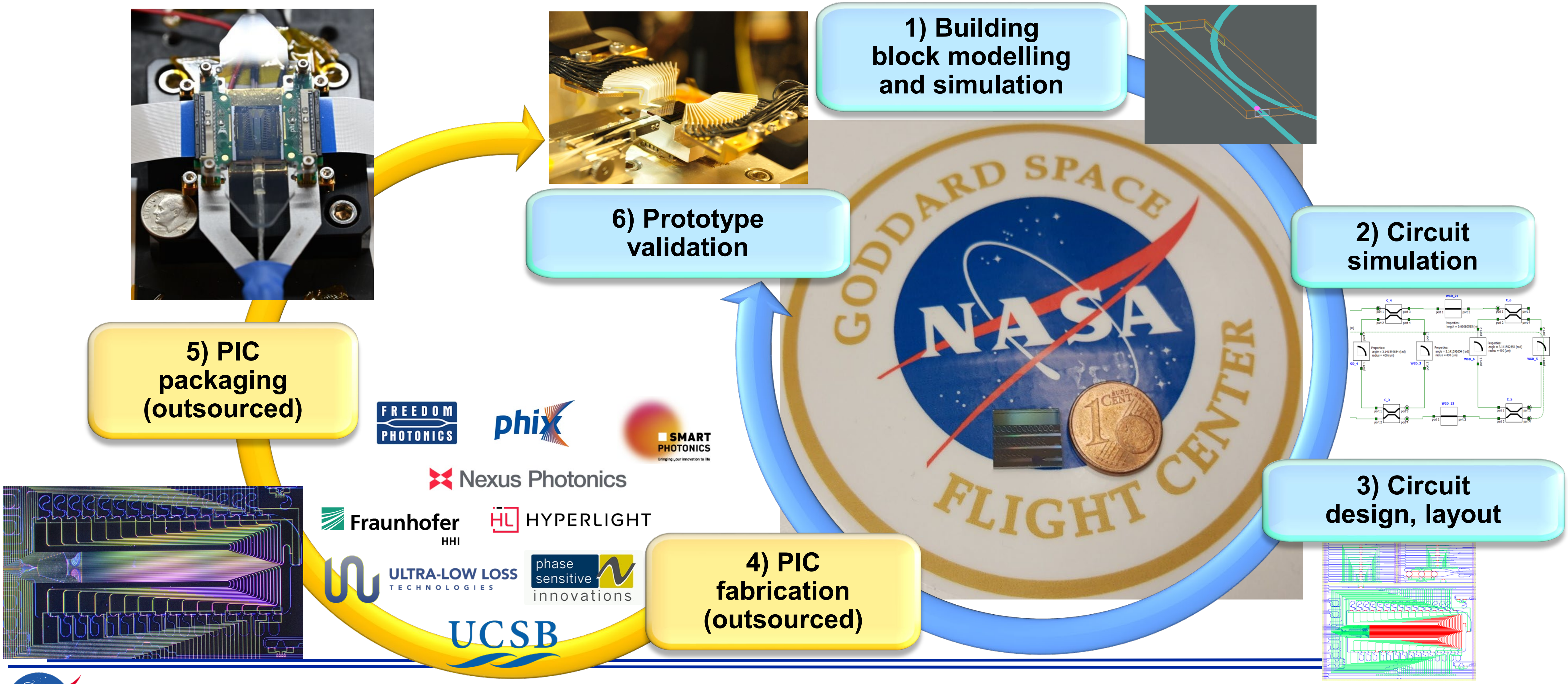
- **PIC technology creates a versatile and scalable platform and opens the door to new capabilities across multiple industries while addressing critical challenges in energy consumption and performance limitations.**

Photonic integrated technology platforms (examples)

Substrate	Properties	Components	Maturity
Silicon Photonics (SiPh)	CMOS compatibility, High index contrast, Mature fabrication	Splitters, Couplers, Gratings, AWGs, Optical filters, Resonators, High-speed modulators (with doping), Photodetectors (with Ge integration)	High
Silicon nitride (SiN)	Ultra-low propagation loss, Wide transparency window	Splitters, Couplers, Gratings, AWGs, Optical filters, Interferometers, High-Q resonators	High
Indium Phosphide (InP)	Direct bandgap, Active-passive integration	Splitters, Lasers, SOAs, Electro-absorption modulators, Photodetectors	High
Lithium Niobate ($LiNbO_3$)	Excellent electro-optic properties, Low optical loss	Splitters, Ultra-fast modulators, Phase shifters	High
Polymer	Low cost, Simple processing	Splitters, Thermo-optic switches, Modulators	Low
Glass (SiO_2)	Very low loss, Fiber compatibility	Waveguides, Splitters, Couplers, Rare-earth doped amplifiers, Optical filters	High
Aluminum nitride (AlN)	Wide bandgap, Piezoelectric	Resonators, Electro-optic modulators, MEMS integration	Medium

- **Photonic integrated platforms provide specific window of transparency, and they target different markets and applications**
- **Hybrid integration merge functionalities and advantages of different platforms and materials: heterogenous, monolithic, flip-chip bonding are some examples**

Photonic integrated circuit (PIC) in-house capabilities



PIC development and collaboration at NASA GFSC

- Photonic integrated circuits for absorption lidar for Methane and water vapor
  - Collaboration between NASA centers:

NASA Goddard Space Flight Center   NASA Langley Research Center

- M. Stephen/550 is the Small Business Technology Transfer (STTR) Photonic Integrated Circuits subtopic manager
  - Participating centers in this subtopic: NASA GSFC, NASA LRC and NASA GRC

- Collaboration between NASA Goddard Space Flight Center and Freedom Photonics (A Luminar Company) to create packaging solutions for photonic integrated circuits suitable for space qualification

- Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS)
  - PI: G. Yang/554 - Photonic integrated circuits for 1030 nm lasers

PIC development and collaboration at NASA GFSC

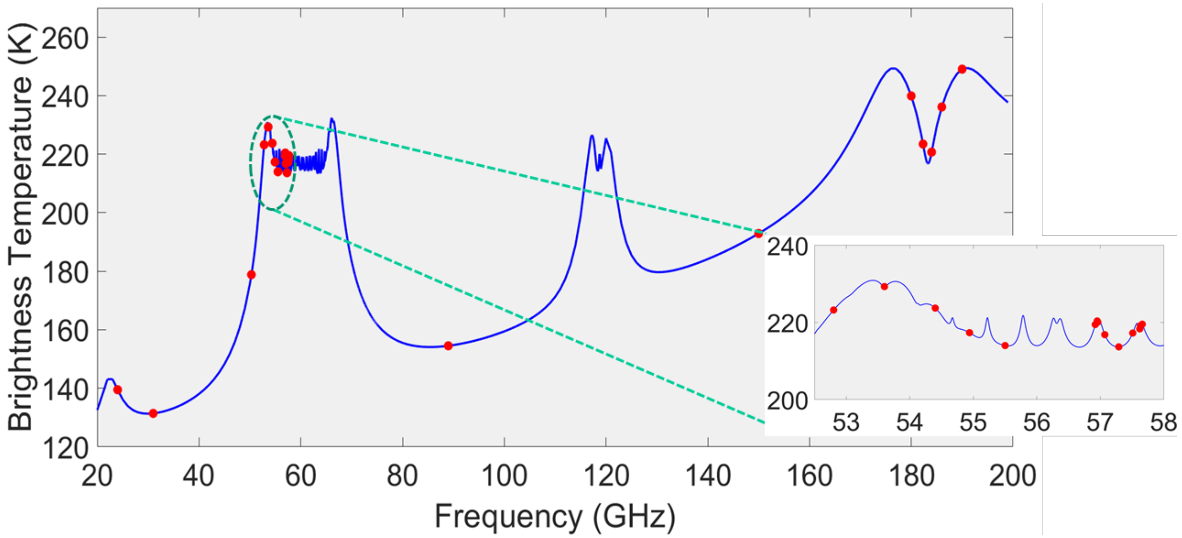
- "Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)" - The first demonstration of hyperspectral microwave instrument based on PIC technology: https://esto.nasa.gov/project-selections-for-iip-21/#Gambacorta

- "Developing the NOAA Next Generation Hyperspectral Microwave Sensor (HyMS): Instrument Concept and Demonstration of Benefits for the NOAA Mission" https://www.nesdis.noaa.gov/news/noaa-awards-joint-venture-program-broad-agency-announcements

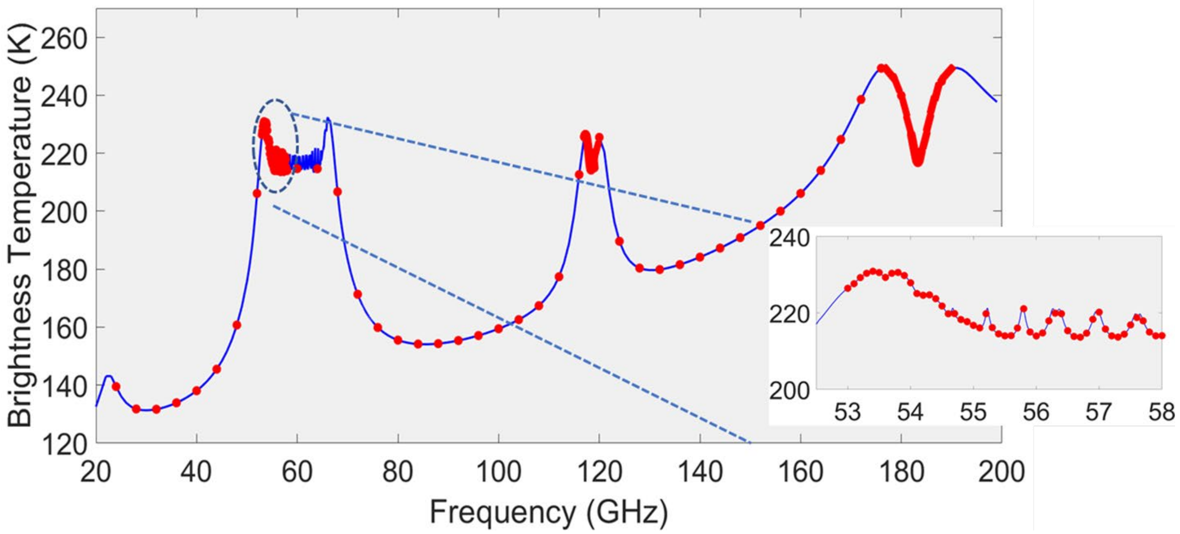
- "The Advanced Ultra-High Resolution Optical RAdiofrequency (AURORA) Pathfinder" – June 2025. NASA Goddard Space Flight Center + Private industry & Academia

What PIC can do

MW technology:



MW + PICASIC technology:



- **ATMS (PoR):**
  - **~20 sparse channels (not contiguous spectrum)**
  - **Missing critical information**
  - **Large SWaP-C**

- **PIC enabled hyperspectral MW technology:**
  - **Contiguous spectrum coverage**
  - **Hyperspectral resolution: 10 MHz (or lower!) with support of ASIC**
  - **Limited SWaP-C**

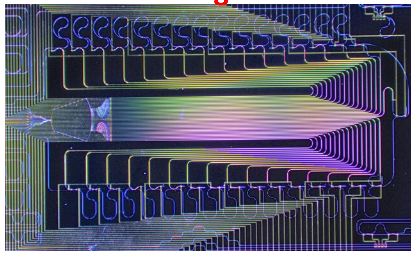
❖ ***HyMPI is agnostic to the MW spectrum so it can be used in different missions (i.e.: Earth, planetary, …) and can serve multiple scientific targets***

The Hyperspectral Microwave Photonic Instrument (HyMPI)

- **HyMPI has been developed in response to the technological stall presented by the microwave systems in terms of size, weight, power consumption and costs (SWaP-C) as well as bandwidth coverage and number of channels**
- **The core of the instrument is based on photonic integrated circuits (PIC) to minimize SWaP-C of the instrument**
- **PICs + ASICs = "PICASIC": full, contiguous, hyperspectral resolution (thousands of channel) ultra-wideband coverage**
- **HyMPI is modular. Each module provides a simultaneous 40 GHz PBL spectrum coverage**
- **It can be applied to multiple parts of the spectrum to obtain full coverage of the MW domain**

Technology	Impact
Microwave (MW)	Capture Earth's PBL thermal radiation
Photonic integrated circuit (PIC)	Ultra-wideband signal processing Minimize SWaP Tunable channels
High speed electronics	Hyperspectral resolution spectra analysis

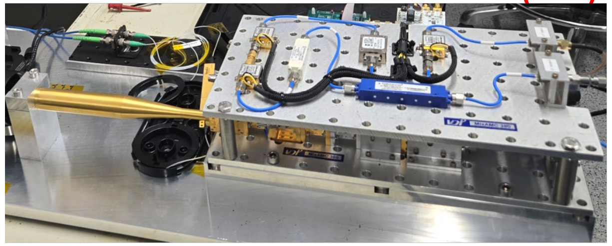
Photonic integrated circuit:



12.5 mm (0.5")

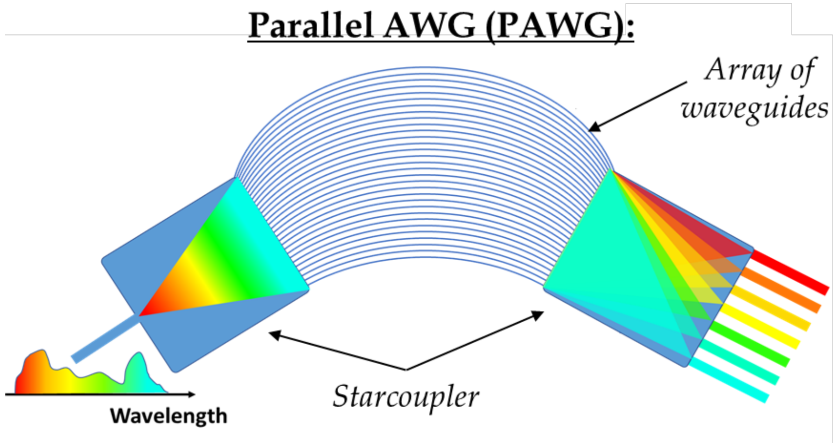
20 mm (0.8")

160 – 200 GHz antenna and front-end (MW)



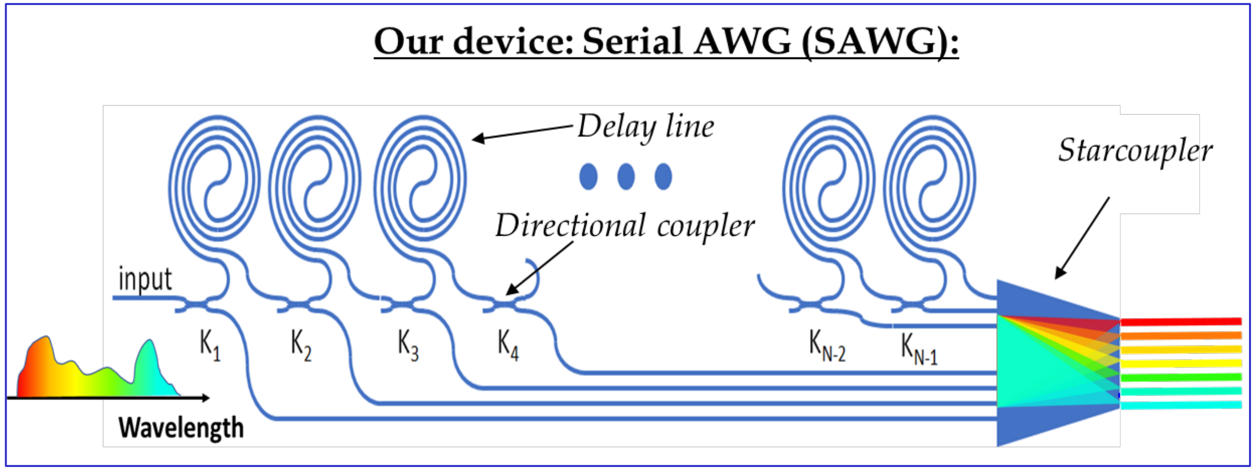
Quad-channel ASIC board (Electronics)

HyMPI: SAWG filter



In a (parallel) Arrayed Waveguide Grating (AWG):

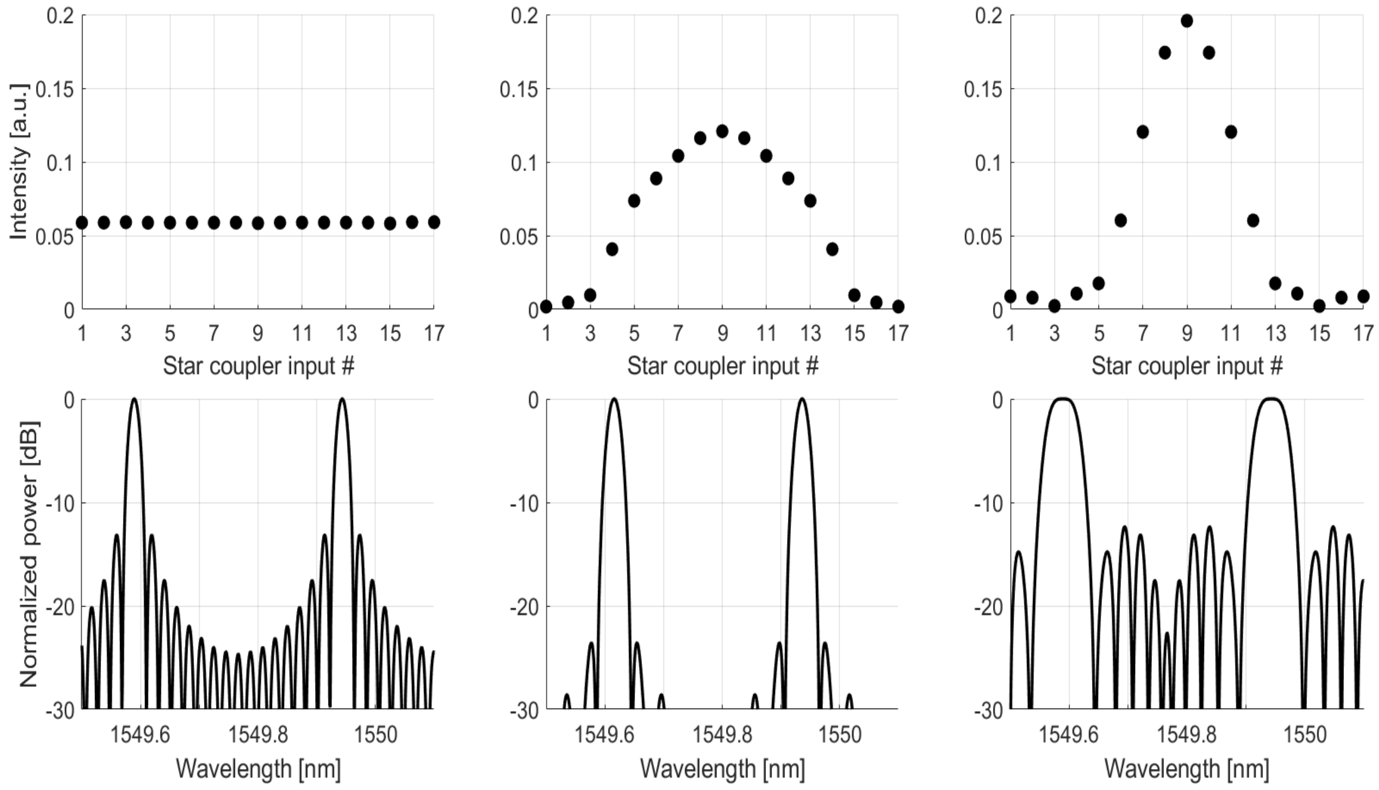
- The first star coupler divides the input power with Gaussian distribution.
- An array of waveguides provide a different phase delay.
- The second star coupler recombines the signals at the output



- Our device is composed of one delay line, N directional couplers (DC) that routes fractions of the input signal to the star coupler (SC)
- The SC performs the Fourier transform of the input distribution
- The spectral filter response is the Fourier Transform of the intensity distribution (due to the DCs' configurations) at the input of the starcoupler

HyMPI: the SAWG filter

- **The access to the DC's splitting ratios (K_i) enables different filter shapes and can produce a high-rejection flat-top response (impossible in the PAWG configuration)**



Examples of three different input intensity distributions at the star coupler

Examples of three different spectral response of the filter

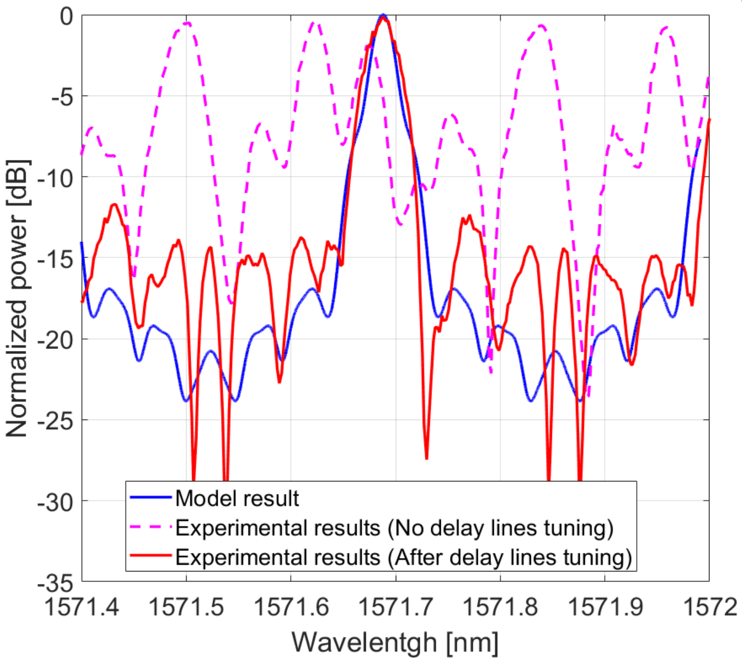
❖ ***The SAWG enables multi-channel filters with improved spectral shape:***
- ***side-mode suppression***
- ***channel selectivity***
- ***flat-top response***

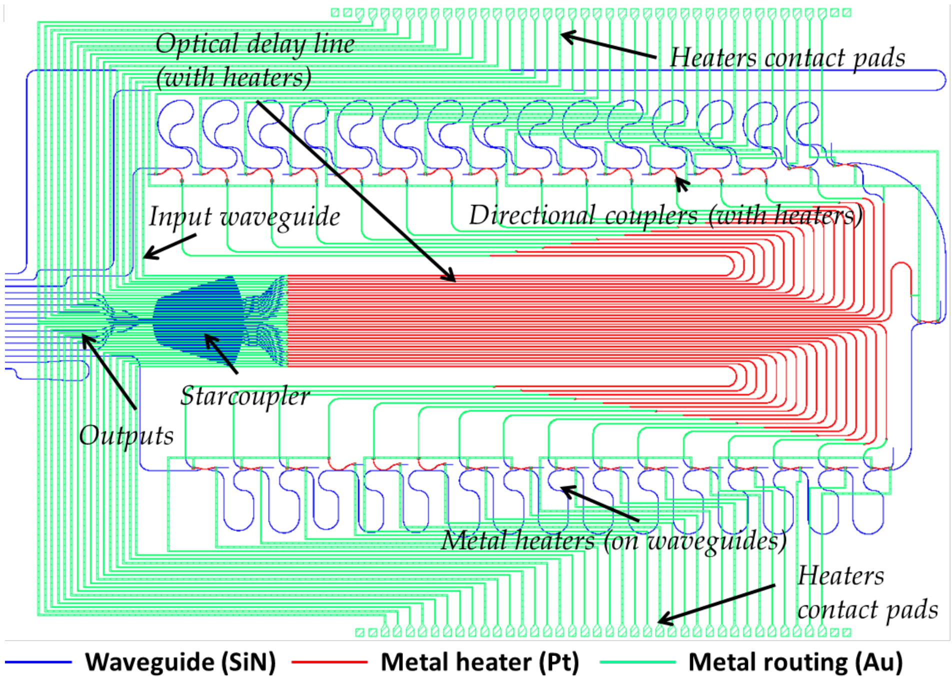
➔ ***Without increasing the number of waveguides in the array***

HyMPI: the SAWG filter

- **For ultra-dense (few GHz channel separation) and narrow (few GHz) bandwidth multi-channel filters, the fabrication inaccuracies impact the phase delay of the signals at the input of the star coupler**
- **It is necessary to correct the phase by changing the refractive index of the waveguides**

SAWG phase delay compensation example:





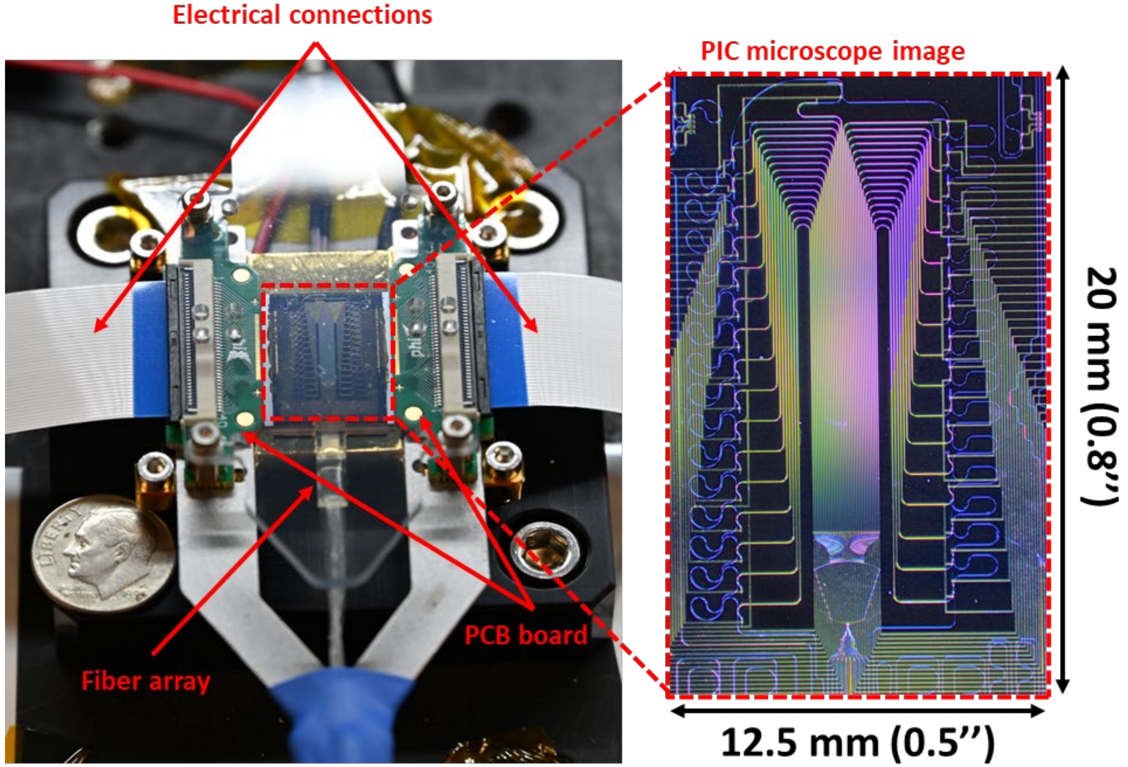
Design:

- 33 Tunable DCs and 33 delay line electrical control **(not all are required, it depends on the fabrication inaccuracies)**
- Heaters designed to maximize thermal and electrical efficiency and minimize thermal xtalk
- Designed to ease the packaging of the PIC

Goals:

- Channel separation: 4.0 GHz
- Channel bandwidth: 2.5 GHz
- Side-lobe rejection: 20 dB

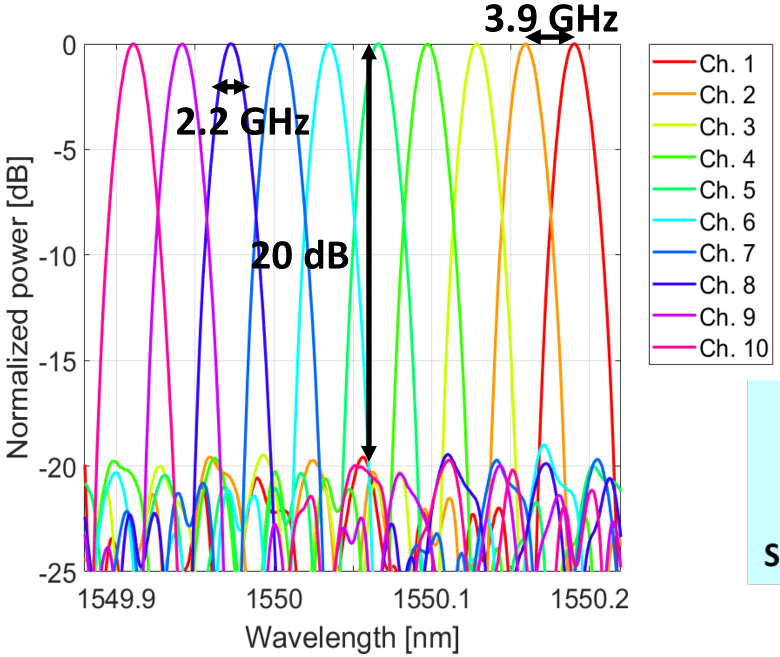
HyMPI: the SAWG filter

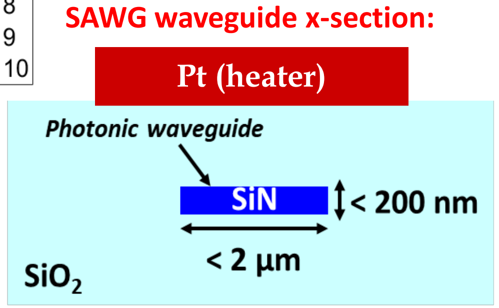


US Patent 11852864 – Title: Serial Arrayed Waveguide Grating

Gambini, et al., 2024, doi: 10.1109/JLT.2024.3349932

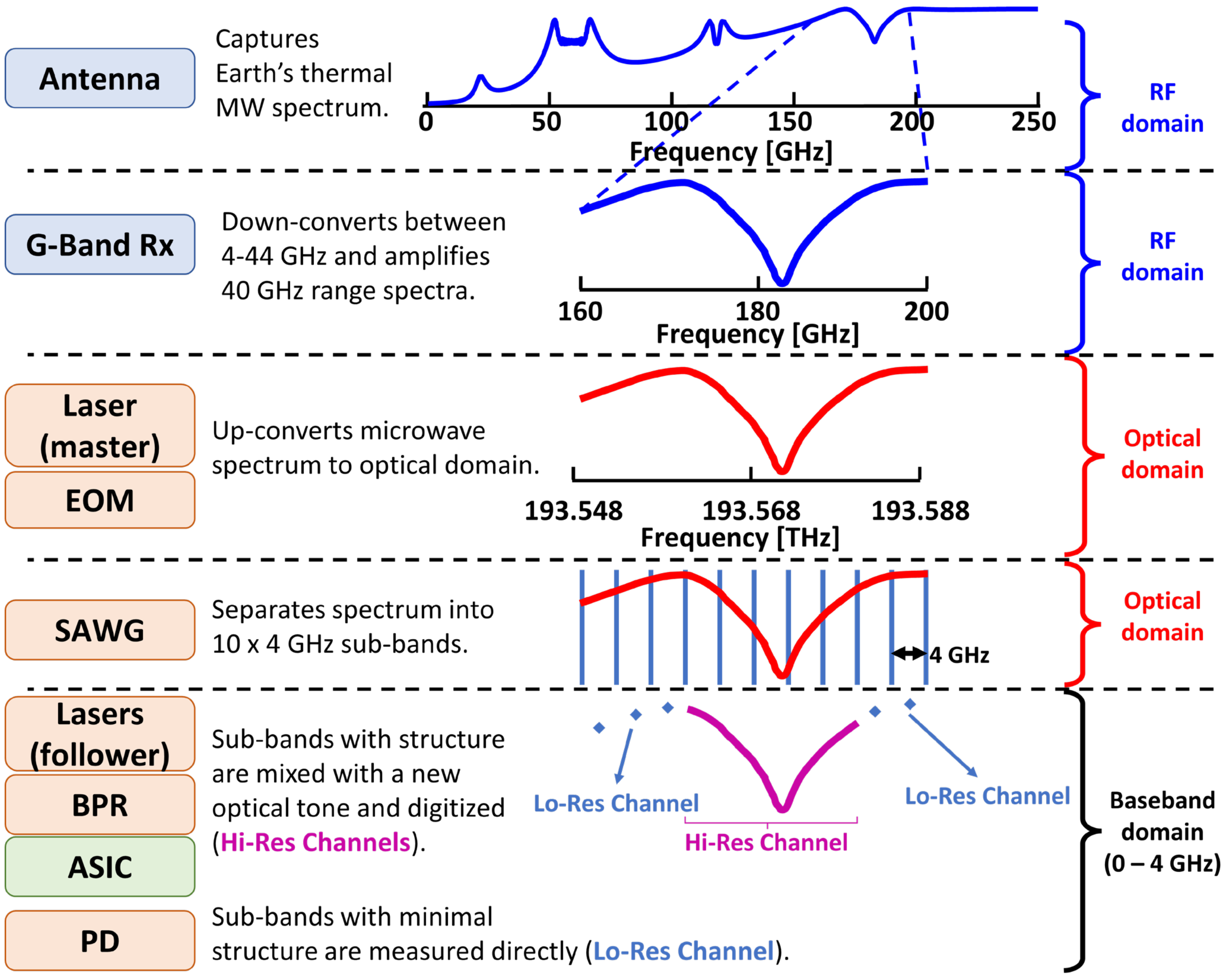
The SAWG divides the upconverted microwave spectrum (in the optical domain) in 10 narrowband channels





- ❖ *SiN platform was chosen because it enables:*
  - *Low optical propagation loss*
  - *High temperature stability ➔ channel frequency stability (important for scientific goals)*

The Hyperspectral Microwave Photonic Instrument (HyMPI)



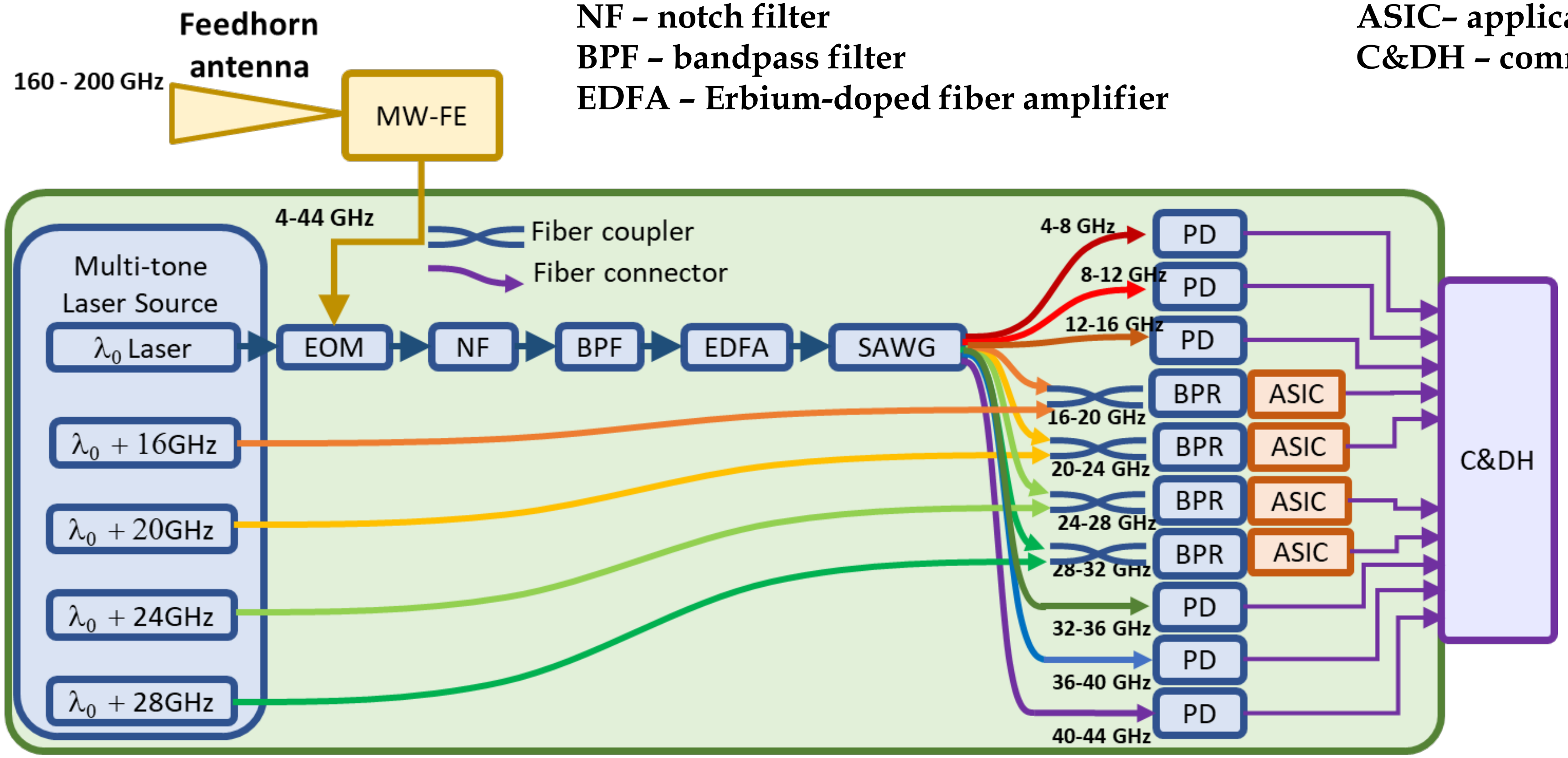
- **The 160 – 200 GHz region was selected to demonstrate the technology**
- **The photonic technology is <u>agnostic</u> to the spectral region and different photonic modules can cover the entire 200 GHz spectrum**
- **The core of HyMPI is a photonic integrated Serial Arrayed Waveguide Grating (SAWG) in SiN platform**

<u>Legend:</u>
Rx: receiver -
EOM: electro-optical modulator -
SAWG: serial arrayed waveguide grating -
BPR: balanced photoreceiver -
ASIC: application specific integrated circuit -
PD: photodiode

HyMPI: Photonic link diagram

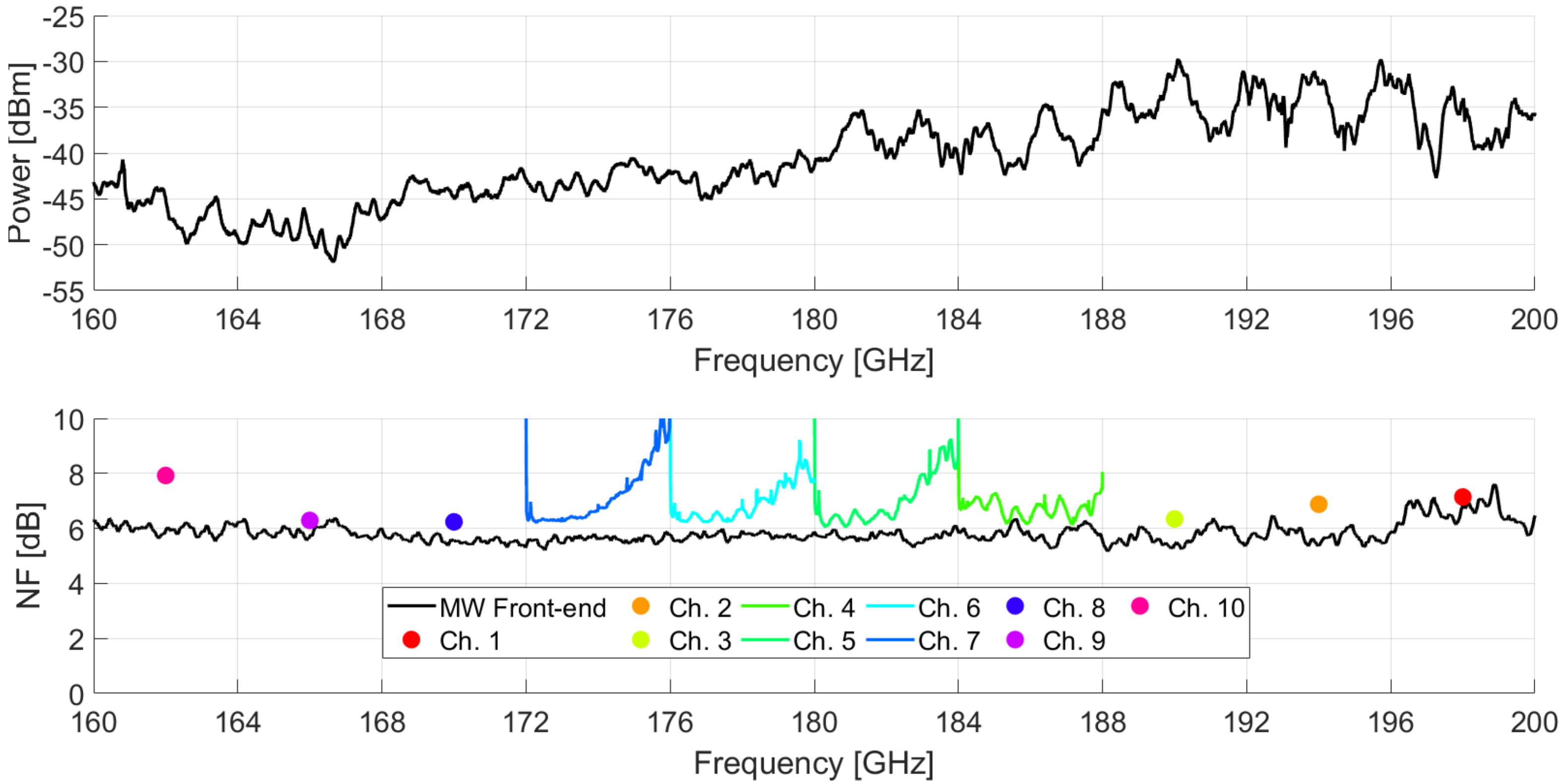
MW-FE – microwave front-end
EOM – electro-optic modulator
Multi-tone Laser source
NF – notch filter
BPF – bandpass filter
EDFA – Erbium-doped fiber amplifier

SAWG – serial arrayed waveguide grating
PD – photodetector
BPR – high-speed balanced photo-receiver
ASIC– application specific integrated circuit
C&DH – command and data handling



- *The HyMPI team engineered a single architecture for simultaneous super- and hyper-spectral resolution measurements*
- *Through hybrid platform the photonic link can be integrated on a single substrate*

HyMPI: Noise figure performance



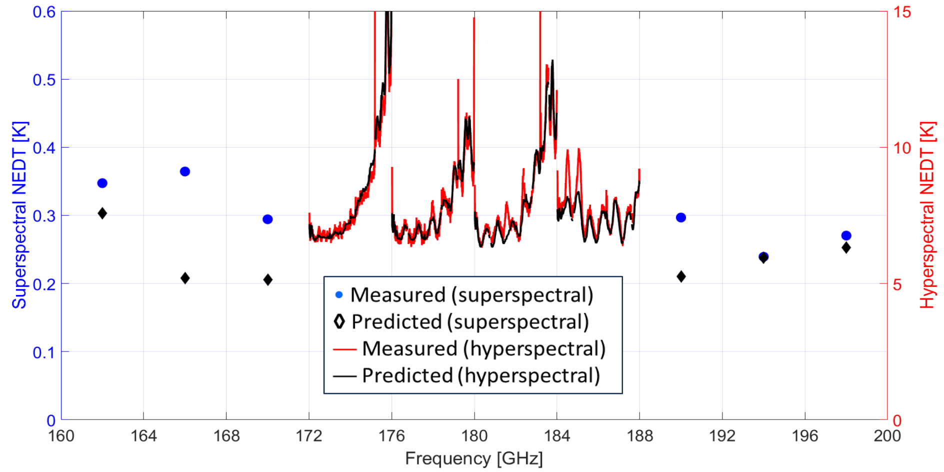
- **The noise figure (NF) of the channels is affected by the front-end gain**
- **Hyperspectral channels, after 2.2 GHz, exhibit higher NF due to the combination of SAWG channel cut-off and follower laser alignment**
- **The NF of the front-end is added as a reference**

❖ *The photonic link* ***does not*** *increase the noise figure of the system significantly*

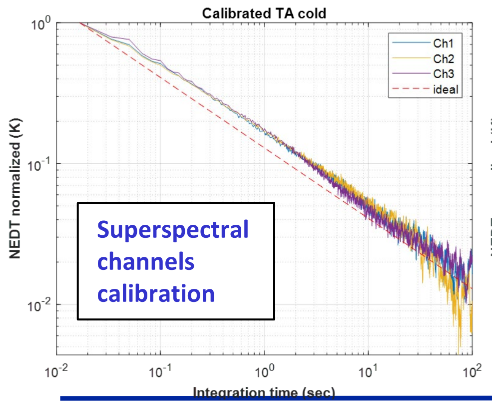
- *Torres, et al., «Noise Figure Characterization of the Hyperspectral Microwave Photonic Instrument (HyMPI)», Photonics Technology Letters, 2025 (submitted and waiting for final publication)*

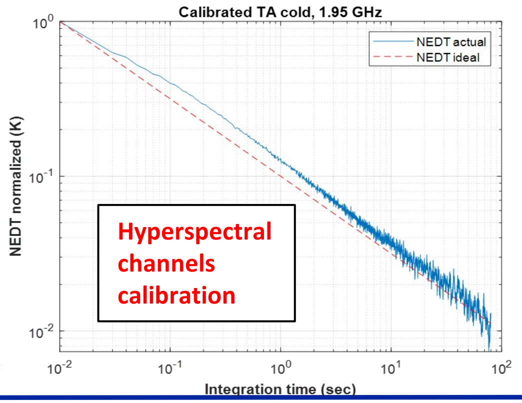
HyMPI: Noise figure performance

- **HyMPI system performance demonstrated a 40 GHz frequency range with simultaneous super- and hyper-spectral resolution channels**



- ***Very good*** ***agreement between expected and measured NEDT measurements***
- ***HyMPI's superspectral channels improve the performance in the Program of Records (ATMS: 0.39 K @ 3 GHz – 18 ms)***
- ***HyMPI's hyperspectral channels add less than 4% of NEDT error***



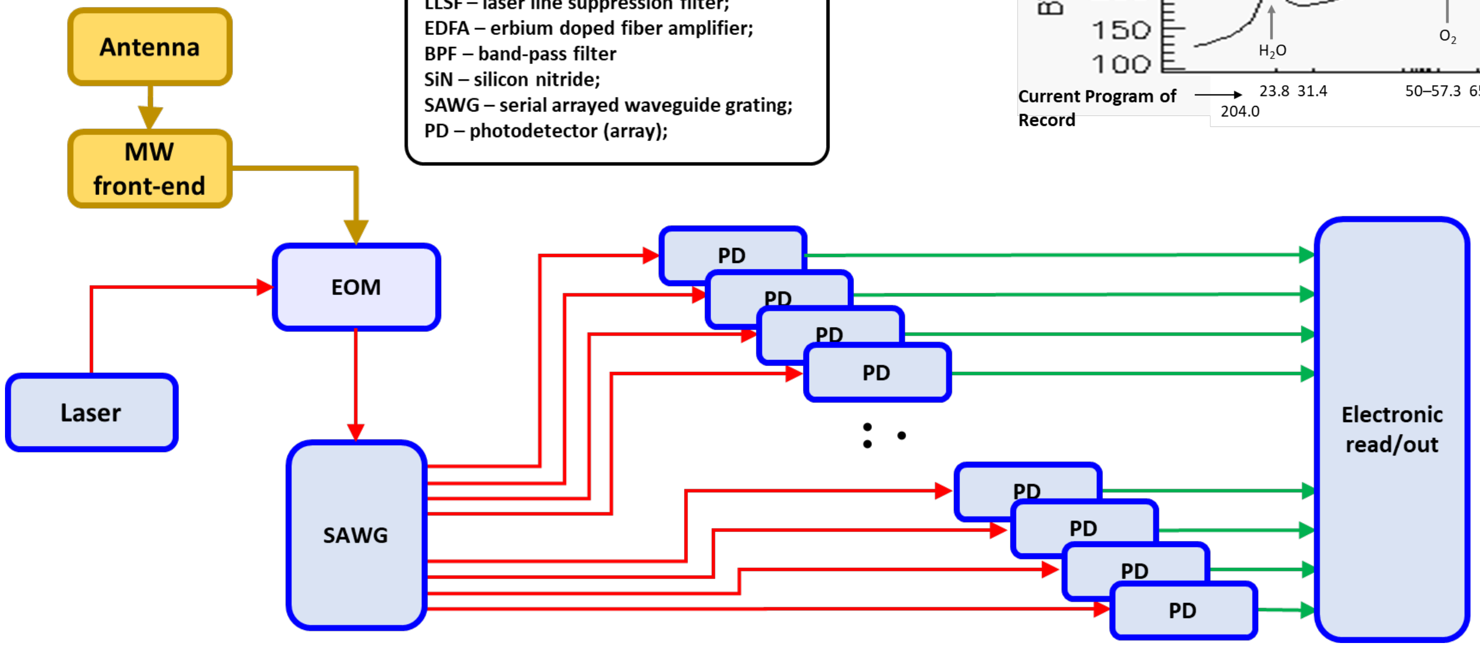


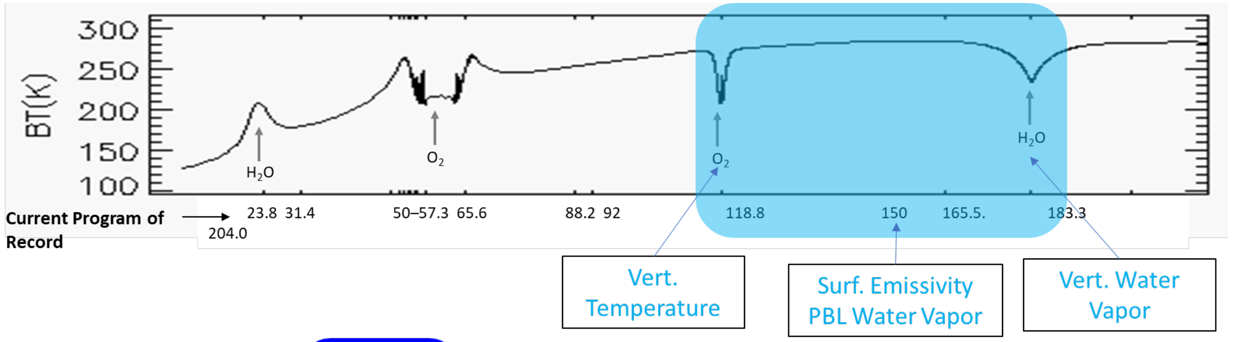
- ***Chopping reduces the impact of 1/f noise on calibration***
- ***After calibration, results improved, data averaged down in time to almost 100 sec***

The Advanced Ultra-high Resolution Optical RAdiofrequency (AURORA) Pathfinder

- The lessons learnt from HyMPI are now used in AURORA Pathfinder
  - NASA ESTO founded space-based technology demonstration of broad-spectrum and hyperspectral microwave photonics-based sounders to support future NASA science missions
  - Principal investigator: Dr. Antonia Gambacorta - NASA GSFC + Private sector & Academia

Legend:
DFB – distributed feedback;
EOM – electro-optic modulator;
LLSF – laser line suppression filter;
EDFA – erbium doped fiber amplifier;
BPF – band-pass filter
SiN – silicon nitride;
SAWG – serial arrayed waveguide grating;
PD – photodetector (array);





- AURORA aims at demonstrating in space:
  - PIC technology: targeting the PBL window channels (superspectral resolution)
  - ASIC spectrometer technology: targeting the PBL absorption lines (hyperspectral resolution)

Thank you

fabrizio.gambini@nasa.gov

List of acronym

Acronym	Description
PIC	Photonic Integrated Circuit
RF	Radio-frequency
CMOS	Complementary Metal-Oxide-Semiconductor
EIC	Electronic Integrated Circuit
STTR	Small Business Technology Transfer
CASALS	Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System
HyMS	Next Generation Hyperspectral Microwave Sensor
AURORA	Advanced Ultra-High Resolution Optical RAdiofrequency
SWaP-C	Size, Weight, Power onsumption and Cost
ASIC	Application Specific Integrated Circuit
ATMS	Advanced Technology Microwave Sounder
PoR	Program of Record
HyMPI	Hyperspectral Microwave Photonic Instrument
PAWG	Parallel Arrayed Waveguide Grating
SAWG	Serial Arrayed Waveguide Grating