The Hyperspectral Microwave Photonic Instrument (HyMPI)

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Introduction

- Microwave (MW) sounders like AMSU and ATMS represent the primary source of information for Numerical Weather Prediction for their capability to sound atmospheric temperature and water vapor under all-sky conditions.

- The 2017 Earth Science Decadal Survey recommended that NASA create a new Incubation Program to explore and develop new technologies to probe the Earth's planetary boundary layer (PBL) by 2027.
  - In response to this initiative, our team at Goddard Space Flight Center has initiated the development of a hyperspectral microwave sensor.

- This presentation describes our effort at NASA's GSFC to overcome limits of RF technology and propose a new technology concept to overcome stalled progress in MW technology.

- This is an application of photonic integrated circuits to MW Earth Remote Sensing.

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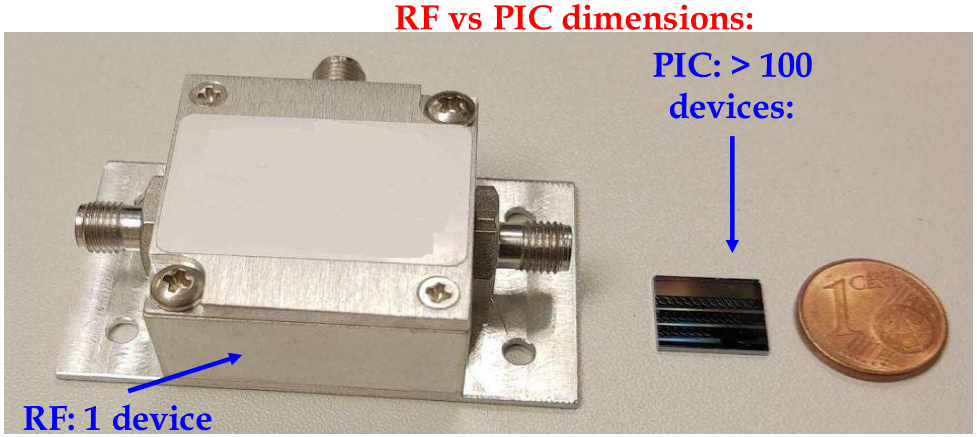
Integrated photonics

- **Integrated photonics: emerging branch of photonics in which waveguides and devices are fabricated as an integrated structure onto the surface of a flat substrate**
  - **The carrier of the signals are photons (not electrons)**

- **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**



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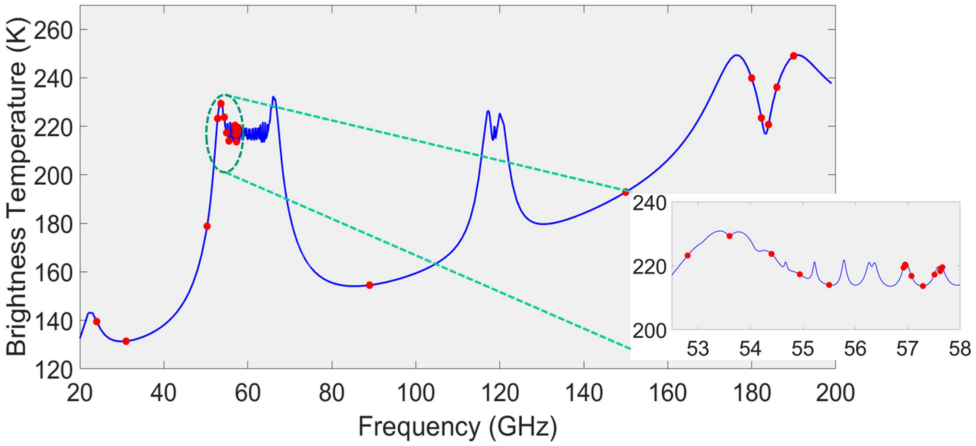
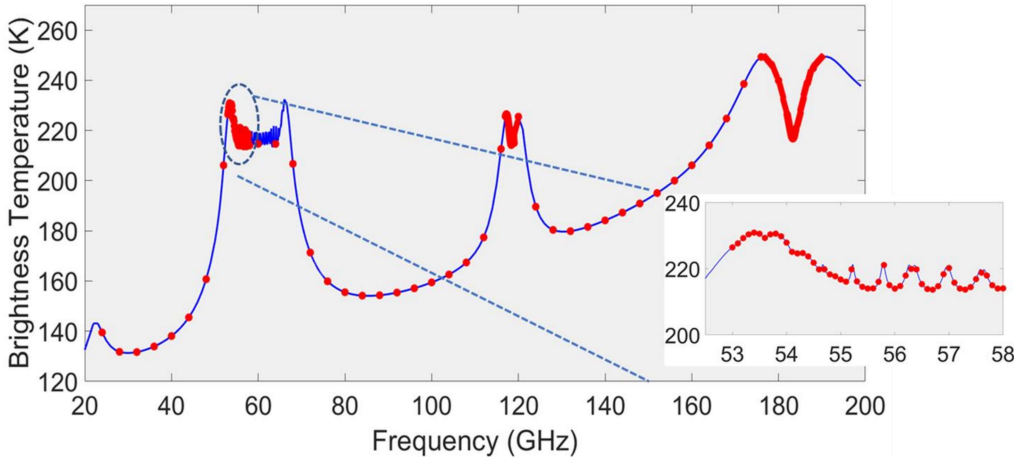
What PIC can do?





- **ATMS**
  - **~20 non-contiguous channels**
  - **Missing critical information**
  - **High footprint and power consumption**
    - **75.4 kg, 10, 200 in^3, 93 W,**

- **PIC enabled hyperspectral MW technology**
  - **Contiguous spectral coverage**
  - **Hyperspectral resolution: 10 MHz (or lower!) with support of Application Specific Integrated Circuits**
  - **Cubesat (27U: 54 kg, 2,700 in^3)**

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The Hyperspectral Microwave Photonic Instrument (HyMPI)

- **HyMPI is being developed to make wideband (~40-GHz,) high-resolution (~20-MHz) measurements of the thermal microwave spectrum.**
  - Hyperspectral evaluation of the microwave spectra will enable more precise characterization of the state of the atmosphere in this key region.
  - This is key to gain a consistent measurement with improved information content in key, highly uncertain variables determining the Earth's radiation budget such as the water vapor continuum, surface emissivity, hydrometeor microphysics and the Planetary Boundary Layer (PBL) thermodynamics with implications for numerical weather prediction and climate science.
- **Our instrument employs photonic integrated circuits (PICs) to enable the parallel processing of the wideband microwave signal.**
  - The use of PIC technology has the potential to improve measurement performance and reduce instrument size, mass and power.
- **Our approach uses an electro-optic modulator to encode the microwave spectra onto an optical signal and then uses photonics to process and channelize the signal.**

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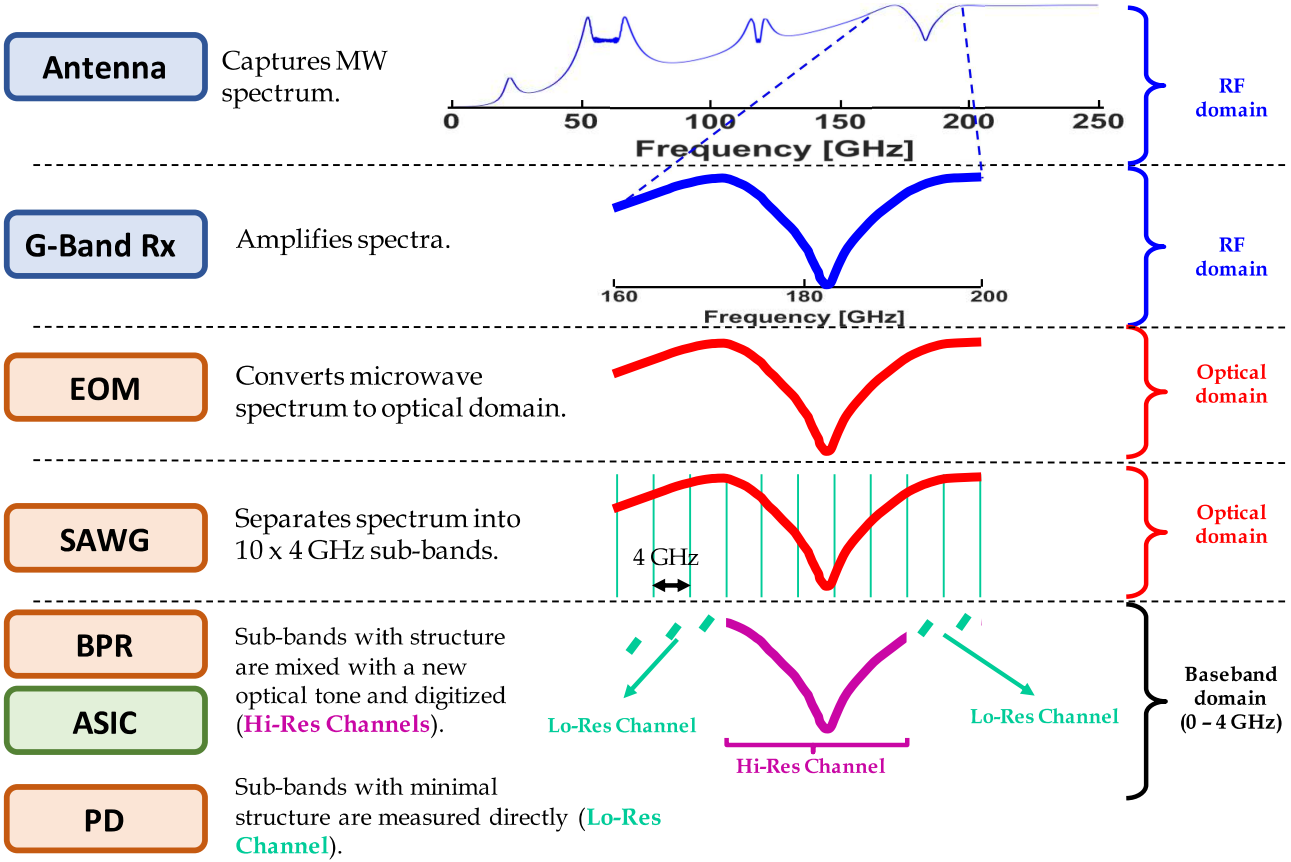
The HyMPI concept



- **HyMPI is based on PICs developed in different platforms (III-V, silicon nitride, …)**
- **HyMPI enables a modular approach**
  - **The single HyMPI system focuses on 40 GHz portion of the MW spectrum**
  - **The PICs allows to use the parallel systems to cover 250 GHz MW spectrum**
- **HyMPI's goal:**
  - **Provide broadband spectral coverage.**
  - **Hyperspectral (thousands of channels, up to 500 kHz resolution) instrument.**
  - **Limited SWaP-C for PBL sensing**

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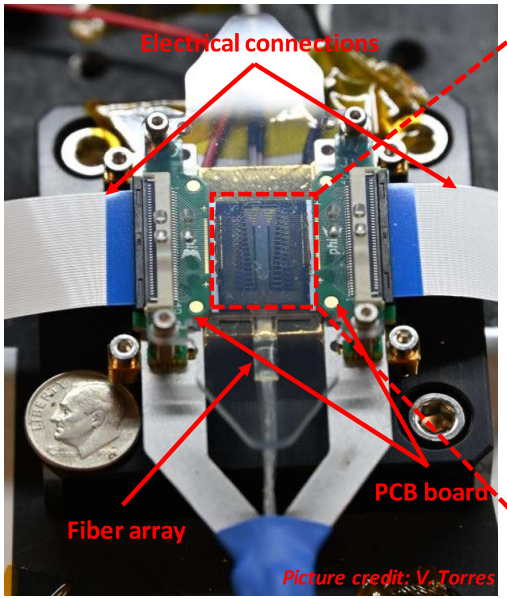
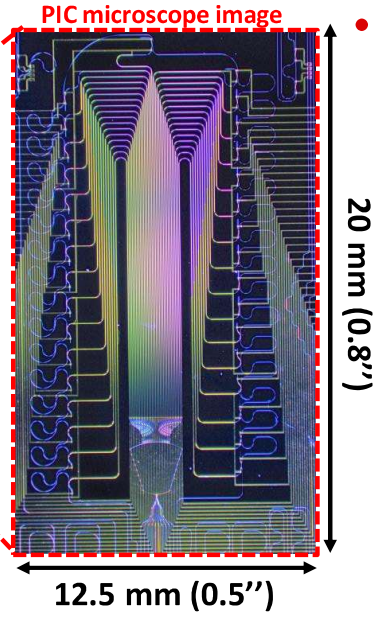
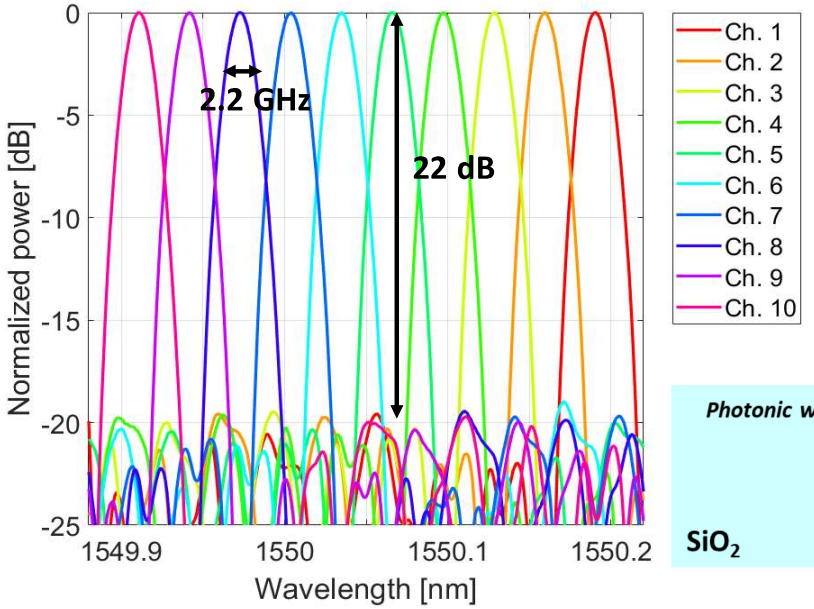
Photonic integrated channelizer

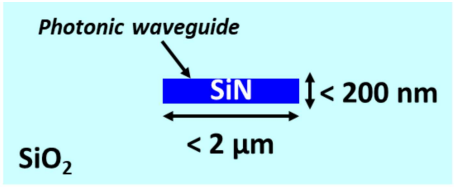
- **The core of HyMPI is an ultra-compact, narrow-bandwidth, and high-density photonic integrated channelizer (Serial Arrayed Waveguide Grating - SAWG) with 10 output ports**





- **The SAWG divides the upconverted microwave spectrum (in the optical domain) in 10 narrowband outputs**





US Patent 11852864 – Title: Serial Arrayed Waveguide Grating

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

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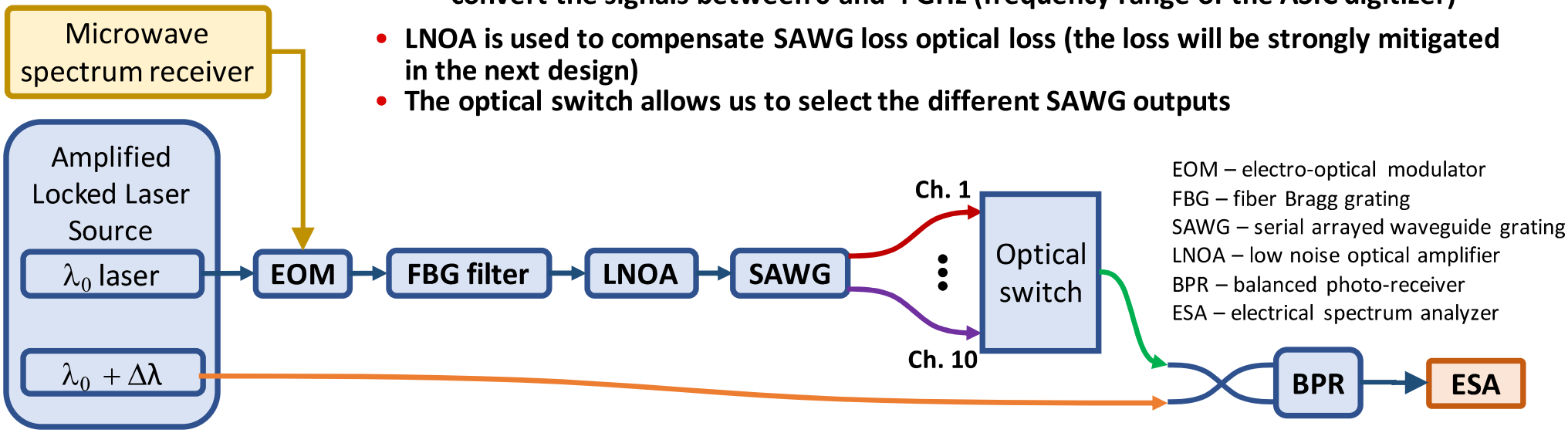
Experimental setup

- **The performance of the HyMPI photonic link has been evaluated with the following experimental setup:**
  - **A multi-tone laser source is under development at Freedom Photonics. We used a locked source with two DFB lasers**
    - **The second DFB laser is always aligned with the SAWG sub-band of interest to down-convert the signals between 0 and 4 GHz (frequency range of the ASIC digitizer)**
  - **LNOA is used to compensate SAWG loss optical loss (the loss will be strongly mitigated in the next design)**
  - **The optical switch allows us to select the different SAWG outputs**



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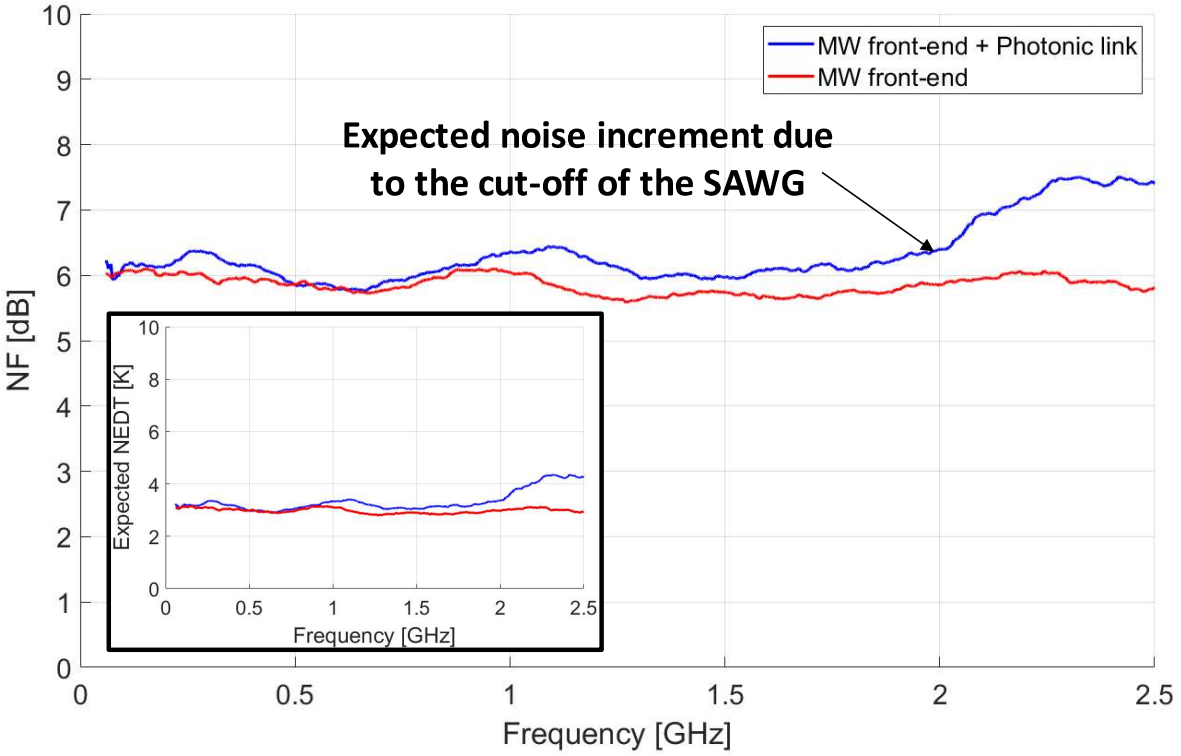
Experimental results

Base-band down-converted channel noise analysis:



- **The noise figure (NF) measurements and prediction of the noise equivalent differential temperature (NEDT) were performed using:**
  - **Resolution: 8 MHz**
  - **Integration time: 18 ms**
- **Measured NF and expected NEDT of the MW front end are: 6 dB and 3 K, respectively**
- **The results show that HyMPI enables <u>hyperspectral resolution sounding without a significant noise increase</u>**

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Conclusions

- **HyMPI enables wide-band, hyperspectral resolution and contiguous spectral coverage without increasing the noise level significantly:**
  - **We demonstrated the capabilities at hyperspectral resolution (8 MHz)**
  - **We demonstrated that the photonic link does not increase the noise**

- **PICs can overcome the limitation of the current MW technology:**
  - **As predicted by our models, PICs do not contribute to the noise of the system**
  - **They can minimize the size, weight, power consumption and costs of the instrument**

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Conclusions

- HyMPI's photonic link is suitable for Earth science, being "limited" by the MW RF technology at this point.
- Going from 22, sparsely sampled channels on ATMS to thousands channels will enable improved retrievals of surface and atmospheric temperature and water vapor.
- Simulated results have shown a 50% improvement in atmospheric temperature and water vapor retrievals, including in the Earth's Planetary Boundary Layer (Gambacorta et al., 2023, doi: 10.1109/JSTARS.2023.3269697)
- HyMPI promises to unveil new horizons in atmospheric science and improved predictive knowledge of climate change, along with enhanced data user's applications of importance for societal benefit, such as improved numerical weather prediction and early warning of extreme events.

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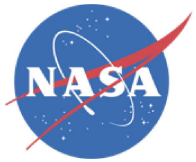
Thank you for your support



Internal Research and Development (IRAD)

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Questions?

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Backup slides

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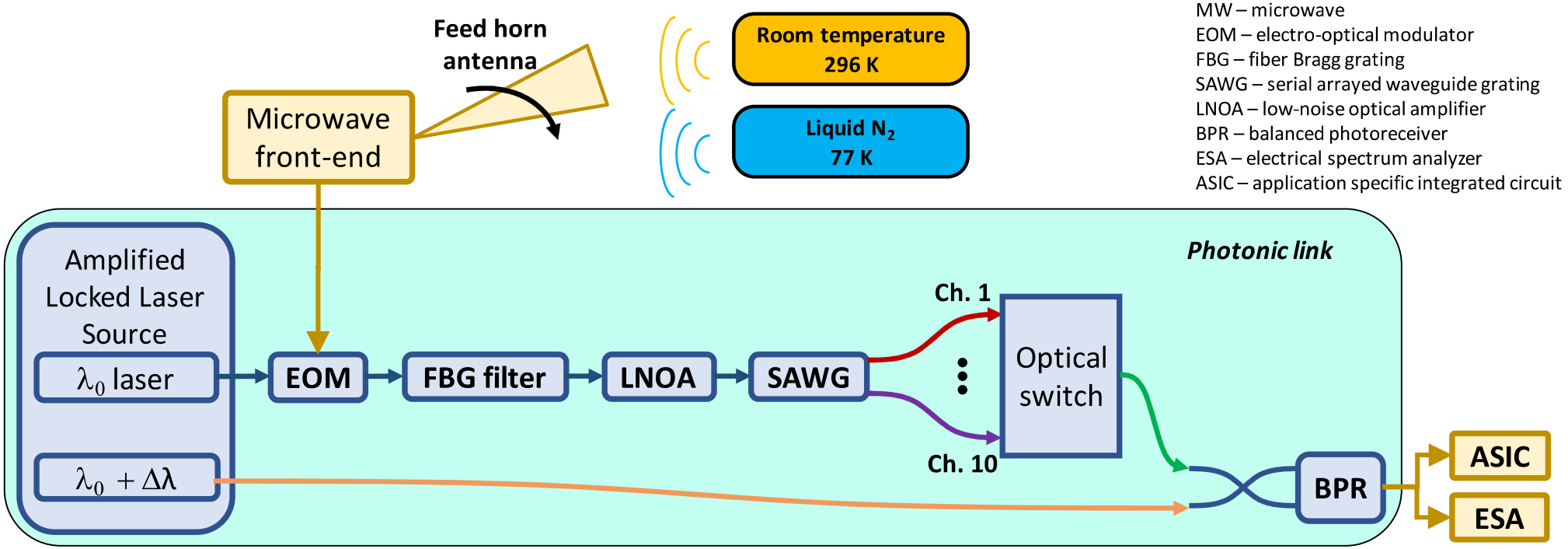
HyMPI System Testing



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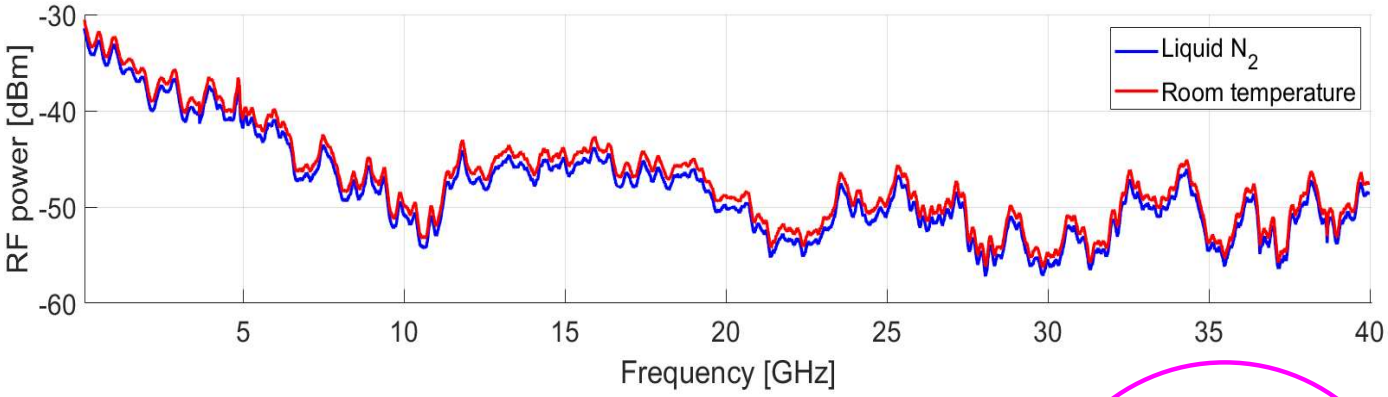
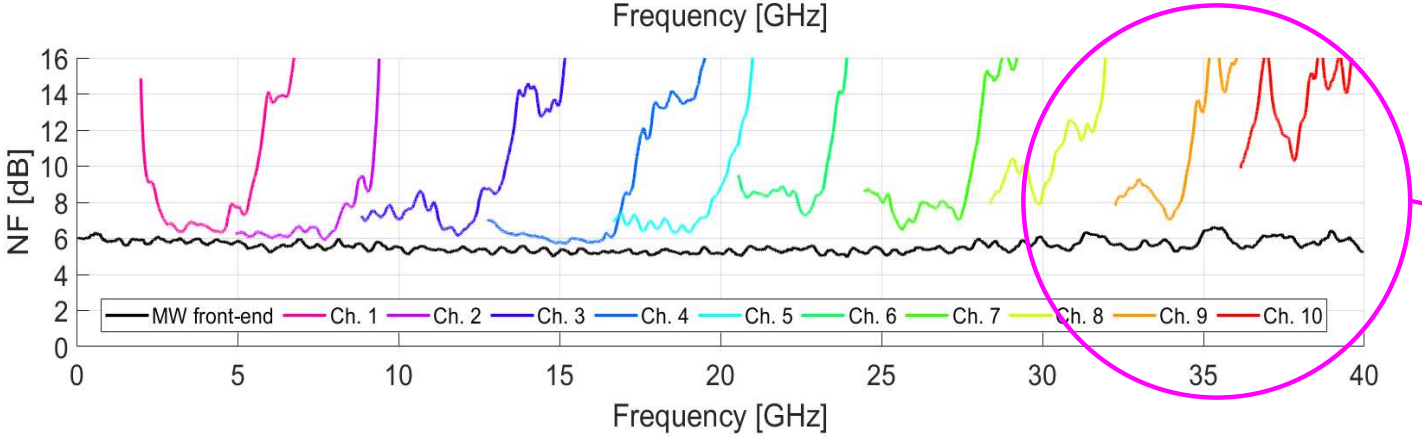
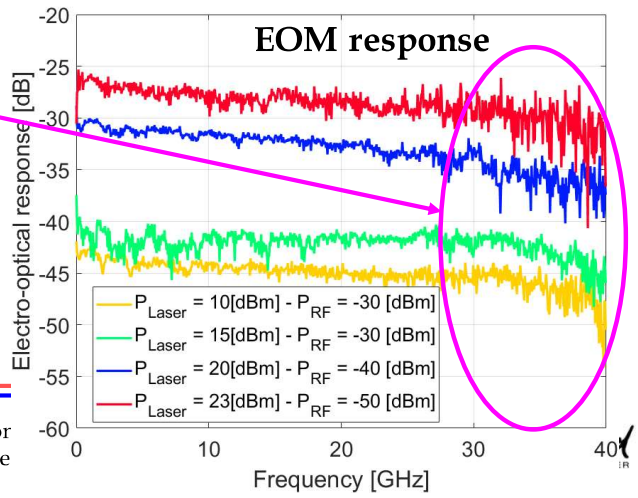




- **The power provided by the front-end is higher for lower frequency**
- **The NF of all the 10 channels has been measured**
  - **The noise figure degrades for higher frequency channels due to the lower power provided by the MW front-end**
  - **And for the roll-off of the phase modulator (f >30 GHz)**



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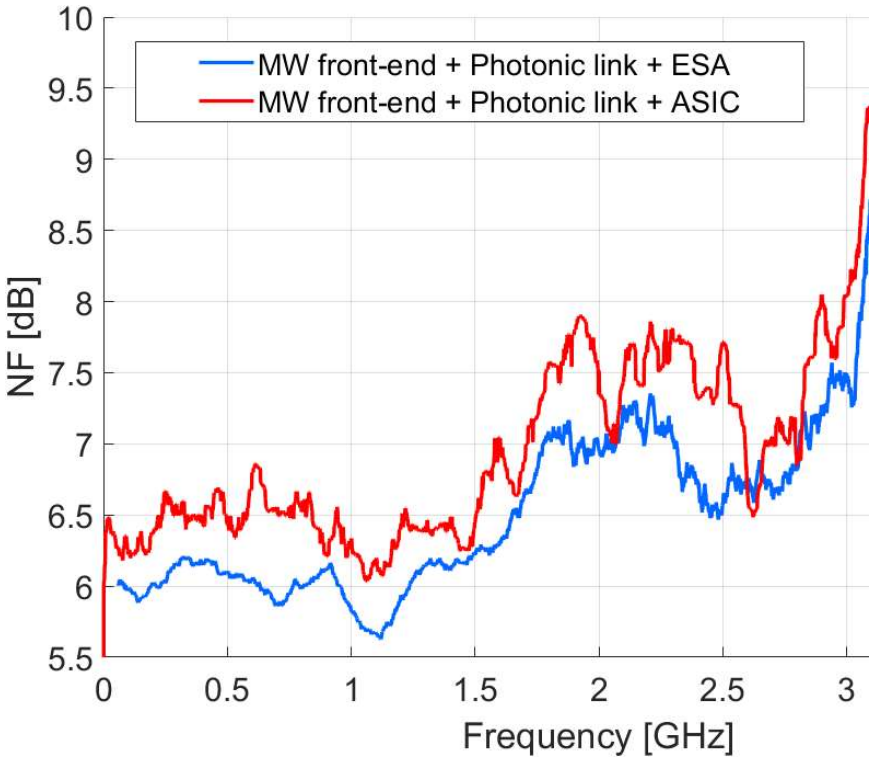
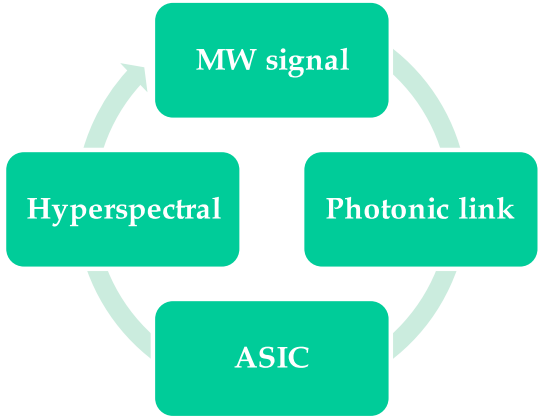
HyMPI System Testing



- **Accomplishment:**
  - **The ASIC was integrated in the system setup**
  - **For the first time we demonstrated the noise performance of the full system for a single hyperspectral channel**
  - **We "closed the loop":**



  - **The ASIC increase the NF of the system of <u>only about 0.5 dB</u>**

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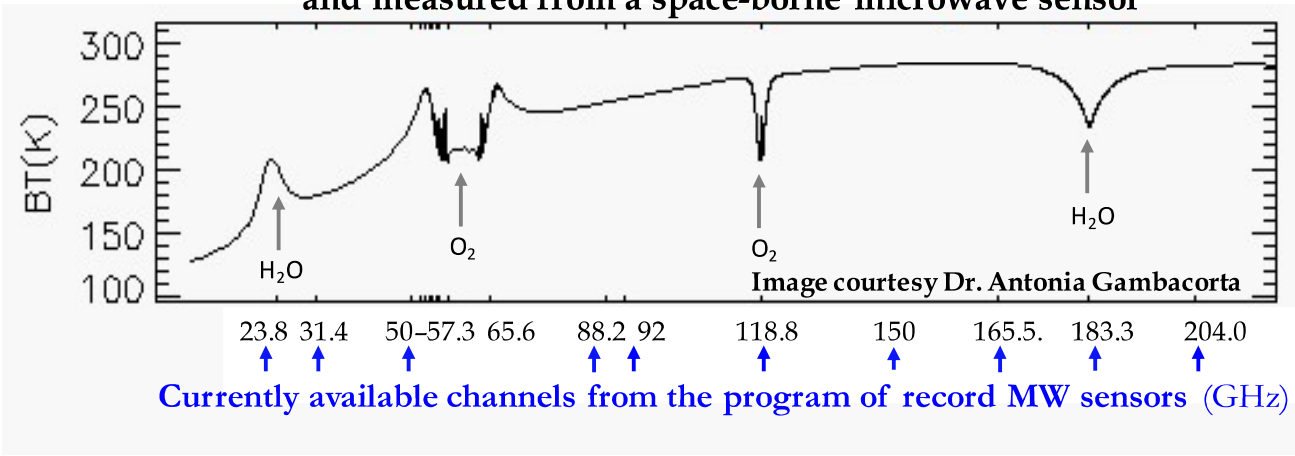
Why Hyperspectral Microwave for Earth's Atmospheric Sounding?

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



- **MW sensors from the current and planned programs have a very limited, sparsely sampled set of channels, leaving a significant part of the spectrum entirely unexploited**

- **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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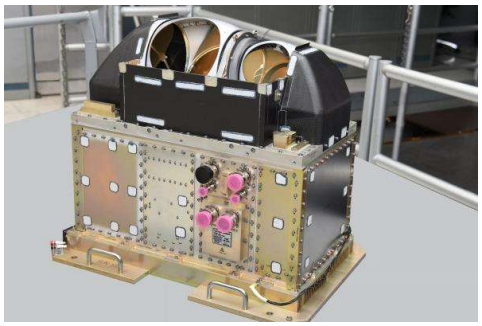
Microwave Technology State of the Art

Radio-frequency systems do not meet science requirements.

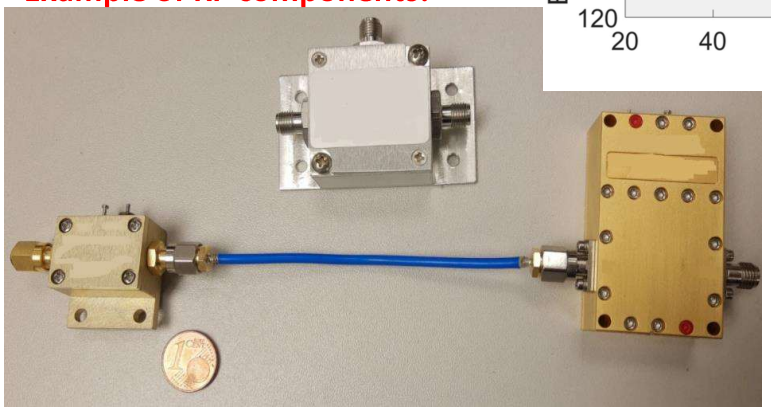
- **Large number of components**
- **High power consumption**
- **Larger size & weight**
- **Limited bandwidth for components**



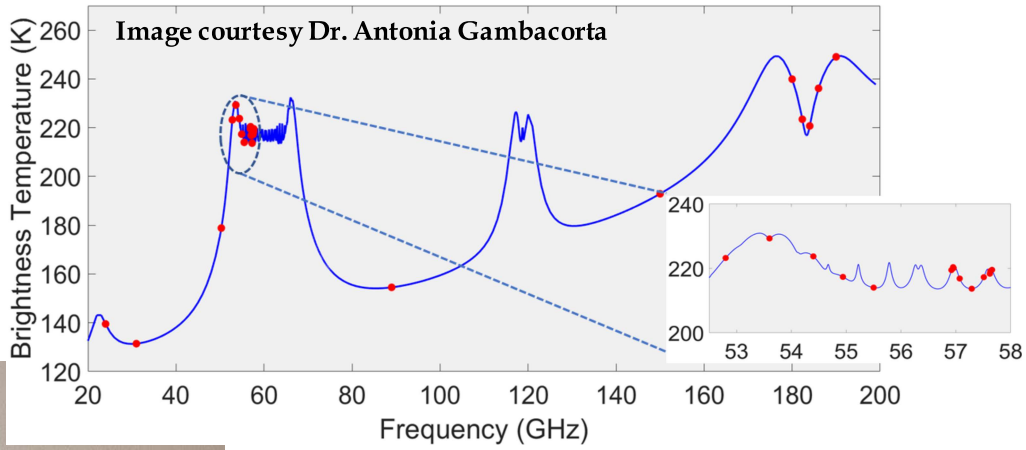
www.nesdis.noaa.gov

Advanced Technology Microwave Sounder (ATMS)

Example of RF components:



Dozen sparsely sampled channels:



The technology limitation

- **Low resolution**
- **Large information loss**
- **Hard to tune**
- **Low level of redundancy**

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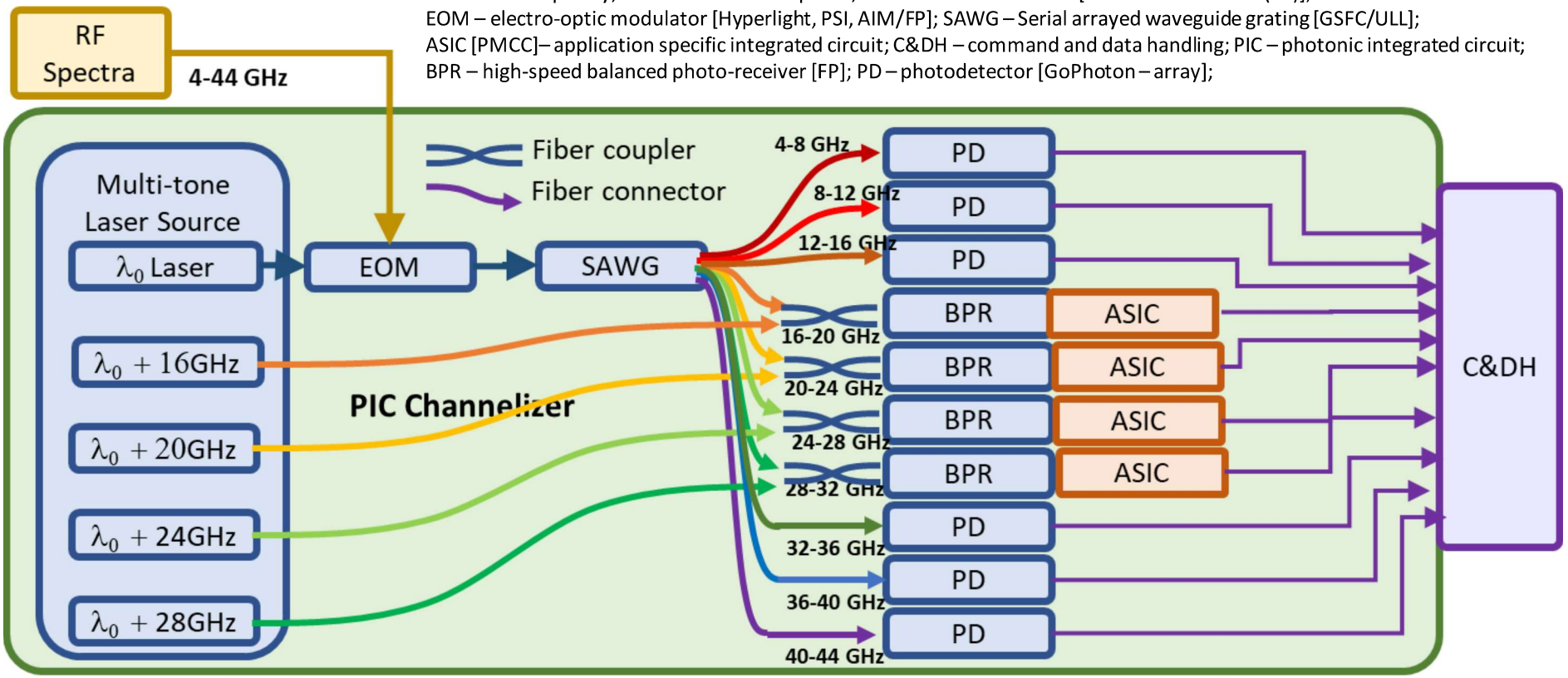
The HyMPI System Diagram

RF – radio frequency; LNA – low-noise amplifier; Multi-tone Laser source [Freedom Photonics (FP)];
EOM – electro-optic modulator [Hyperlight, PSI, AIM/FP]; SAWG – Serial arrayed waveguide grating [GSFC/ULL];
ASIC [PMCC]– application specific integrated circuit; C&DH – command and data handling; PIC – photonic integrated circuit;
BPR – high-speed balanced photo-receiver [FP]; PD – photodetector [GoPhoton – array];



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