

Noise Figure Characterization of the Hyperspectral Microwave Photonic Instrument (HyMPI)

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Abstract— This work demonstrates the noise performance of the photonic back end of a hyperspectral microwave-photonic spectrometer aimed at augmenting the remote sensing capability from space, with a focus on the Earth’s planetary boundary layer (PBL).

Using a distributed-feedback (DFB) laser and an electro-optical phase modulator, a 40 GHz spectrum is upconverted into the optical domain and sent to a 10-channel photonic integrated serial array waveguide grating (SAWG) where the spectra are separated into 4 GHz channels. Spectral content of each channel is downconverted to baseband using a second DFB laser and measured using an electrical spectrum analyzer (ESA) at a resolution of 8 MHz.

Measured results of the end-to-end system Noise Figure (NF) for all channels agree with the theoretical analysis and demonstrate the suitability of microwave photonics for atmospheric studies.

Index Terms—hyperspectral sensors, microwave photonics, photonics, photonic integrated circuits, planetary boundary layer, remote sensing

I. INTRODUCTION

Hyperspectral microwave sensors have been identified as an “essential component” of future planetary boundary layer (PBL) observation systems [1]. Hyperspectral sensors measure many frequency bands providing an almost continuous measurement capability across a broad spectral range. This capability would enable microwave radiometers (MWRs) to produce sounding measurements with increased spectral coverage and resolution compared to conventional sounders (e.g., the Advanced Technology Microwave sounder, ATMS [2]). Traditional radio frequency (RF) technology MWR system design uses a cascade of filters and mixers to down-convert the higher frequencies into narrow, near-baseband channels. Channelizing the spectrum before or after the microwave mixer is a common system design for spaceborne MWRs which restricts the instrument capability to a limited number of sparse channels to minimize size, weight, power consumption and cost [3]. The design complexity, size,

weight and component count required for implementing wideband capability using microwave components make it unsuitable for spaceborne MWRs [4]. In addition, pressure to reduce mission expenses drives the system architecture to reduce size, weight, power consumption, and cost (SWaP-C) [4], [5].

In recent years, the integration of photonics with microwave techniques has emerged as a promising approach to overcome the limitations of the current microwave-based instruments [6]. The advantages provided by photonic technologies include low losses that are frequency-independent; large bandwidth; reduced SWaP-C; and electromagnetic interference (EMI) immunity [7], [8]. The integration of hyperspectral photonics with microwave engineering presents a new solution to improve SWaP-C across various fields, including remote sensing, biomedical imaging, environmental monitoring, and industrial applications [9], [10], [11]. In recent years, the integration of hyperspectral photonics with microwave techniques has emerged as a promising approach to overcome limitations and improve PBL weather prediction [12], [13].

Our first step toward the realization of microwave-photonic hyperspectral radiometers to perform atmospheric temperature and humidity profile measurements is the Hyperspectral Microwave Photonic Instrument (HyMPI) [14]. This technology development aims to develop a novel hyperspectral microwave sensor to augment NASA’s thermodynamic sounding capability from space with a focus on the Earth’s PBL while reducing SWaP-C.

This work presents the HyMPI baseline architecture and will discuss the noise figure performance of the photonic link with its channels configured for hyperspectral measurements.

II. SYSTEM ARCHITECTURE

The Hyperspectral Microwave Photonic Instrument (HyMPI) has three distinct subsystems as shown in Fig. 1: (a) a microwave front-end that captures a 40 GHz portion of the microwave spectra; (b) a photonics link that upconverts the

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microwave spectra into the optical domain, channelizes it and then down converts some channels to baseband; and (c) a data processing back-end that digitizes the 4 GHz channel.

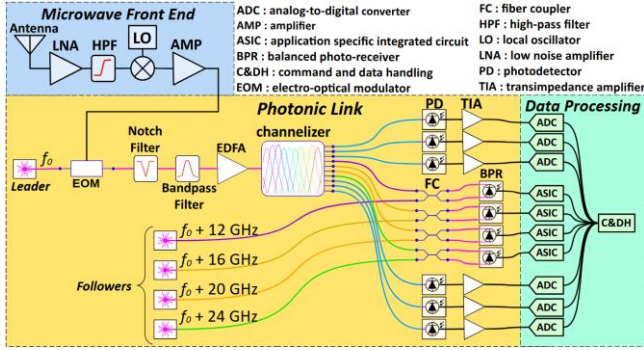


Fig. 1. HyMPI consists of 3 major subsystems: a microwave front end, a photonic link, and an electronics data processing back-end.

A. Microwave Front-End

The microwave front-end consists of a 160 – 200 GHz mixer/amplifier/multiplier chain with a 13.125 – 13.458 GHz pre-multiplier and a series of equalizers and amplifiers to provide higher gain and flatter response over the 40 GHz range. The RF spectra is first downconverted with a 160 GHz local oscillator, and the intermediate frequency (IF) spectra becomes the input to the electro-optic phase modulator (EOM), shown in Fig. 2.

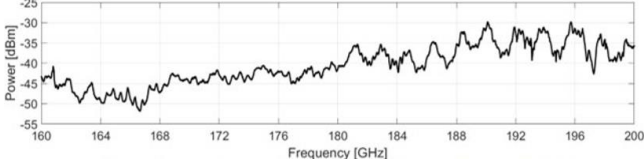


Fig. 2. Output spectra of the RF receiver showing relative flatness over its 40GHz range measured with an electrical spectrum analyzer (ESA).

B. Photonic Link

The microwave spectrum shown above is upconverted to the optical domain using the EOM. Using a DFB laser of frequency f_0 as the pump laser, the EOM is used to encode the incoming microwave signal onto the carrier provided by the pump laser as shown in Fig. 3.

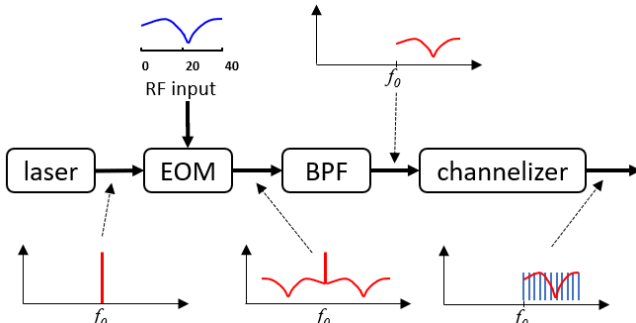


Fig. 3. An RF signal gets upconverted to the optical domain

using a pump laser and EOM.

This process creates optical sidebands equally spaced from the laser carrier by the modulating RF center frequency. Each sideband contains all the spectral components of the modulated signal.

Once in the optical domain, the received signal passes through a bandpass filter to reject the leader laser tone and one of the side bands. The resulting spectrum is then sent to the channelizer.

The core of HyMPI is an ultra-compact, narrow-bandwidth, high-density channelizer based on silicon nitride platform with 10 output ports implemented using a serial arrayed waveguide grating (SAWG) [15]. This photonic integrated circuit (PIC) divides the upconverted microwave spectrum (in the optical domain) in 10 narrowband channels which are about 4 GHz apart [16]. Each channel has a -3dB bandwidth of 2.2 GHz with side-mode suppression of 20 dB, as shown in Fig. 4.

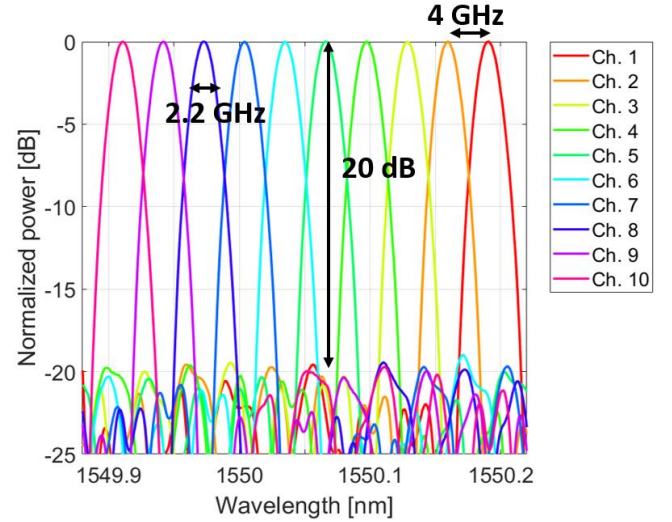


Fig. 4. SAWG spectra shows that each channel has a -3dB bandwidth of 2.2 GHz with side-mode suppression of 20 dB.

The SAWG output channels can be used for hyperspectral measurements with a resolution of 3.9 MHz, or superspectral measurements with a resolution of 4 GHz. The superspectral channels are measured directly using photodetectors and analog-to-digital converters. The hyperspectral channels are mixed with the corresponding follower optical tone and digitized using the spectrometer ASIC. In Fig. 1 the hyperspectral channels are 5, 6, 7 and 8. Therefore, the down-conversion tones have wavelengths of f_0+16 GHz, f_0+20 GHz, f_0+24 GHz, and f_0+28 GHz, respectively. We analyze the noise performance of the photonic link architecture by characterizing the Noise Figure performance of the channels in hyperspectral configuration.

C. Data Processing Back-End

The HyMPI's back-end uses a commercial off-the-shelf (COTS) module [17] consisting of a quad digital spectrometer application-specific integrated circuit (ASIC). Each spectrometer ASIC has an input signal bandwidth (-3dB) of 5.5 GHz, a sampling rate up to 8 GS/s, and a power consumption

of less than 1.6 W of power.

III. EXPERIMENTAL RESULTS

The experimental setup used for the NF measurements of this work is shown in Fig. 5.

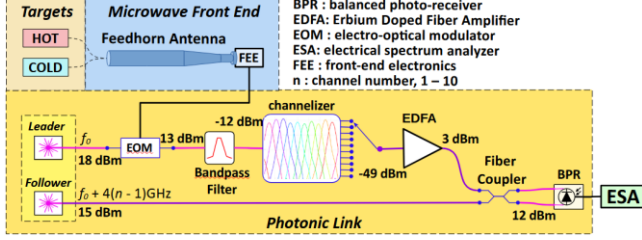


Fig. 5. Experimental setup for NF measurements. The follower laser tone frequency is set to $f_0 + 4n$, where n is the SAWG channel being tested.

The RF front end looked at two different targets: a microwave absorber at room temperature, the “hot” target, and a polystyrene foam container filled the liquid nitrogen (LN₂), the “cold” target. Fig. 6 shows the RF front end time series output of one hyperspectral channel for each target. The received microwave is upconverted to the optical domain using the EOM. The bandpass filter allows the desired sideband to enter the channelizer. An erbium-doped fiber amplifier (EDFA) was used to compensate for power loss of the system. The output of each channel is mixed with the appropriate tone using a tunable DFB laser at the appropriate frequency $f_0 + 4n$, where n corresponds to the number of the channel, for downconversion. The resulting spectrum is measured using a Keysight N9030A signal analyzer with a bandwidth resolution of 8 MHz, and a video bandwidth of 1 kHz.

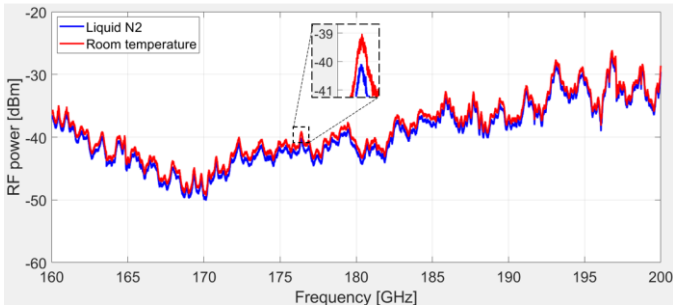


Fig. 6. Spectra of the RF front end for both the hot and cold targets. The insert shows the power difference is 1 dB.

IV. RESULTS

For a receiver with input signal S_i , noise N_i and gain G , the noise figure [18], NF , is given by

$$NF = 10 \log(SNR_i/SNR_o) = 10 \log(N_o/GN_i) \quad (1)$$

Since the noise power is given [19] by $P_N = kT_N B$, where k is Boltzmann’s constant, B is the bandwidth, P_a the noise power, and T will be referred to as the noise temperature. Then the output

noise N_o can be expressed as $N_o = GN_i + N_{eq} = kBG(T_i + T_{eq})$. Then for $T_i = T_{amb} = 296$ K, (1) becomes

$$NF = 10 \log(1 + T_{eq}/296) \quad (2)$$

The noise figure measurement can be performed using a spectrum analyzer and the “Y Factor” technique [20]. The Y factor, Y , is defined as

$$Y = \frac{P_{hot}}{P_{cold}} \quad (3)$$

where P_{hot} and P_{cold} are the receiver’s measured output power for the hot and cold cases, respectively.

Using liquid nitrogen (LN₂) as cold target (80K) and room temperature as hot target (296K) in (2) and applying (3), the noise equivalent temperature of the system becomes

$$T_{eq} = \frac{T_{hot} - YT_{cold}}{Y - 1} = \frac{296P_{cold} - 80P_{hot}}{P_{hot} - P_{cold}} \quad (4)$$

Therefore, (2) becomes

$$NF = 10 \log \left[1 + \frac{296P_{cold} - 80P_{hot}}{296(P_{hot} - P_{cold})} \right] \quad (5)$$

The NF measurements for a hyperspectral channel shown in Fig. 8 and Fig. 9 were calculated using the Y factor method described above, and were performed using a Keysight N9030A signal analyzer with a bandwidth resolution of 8 MHz, a video bandwidth of 1 kHz.

Fig. 7 shows the end-to-end system NF for each individual SAWG channel and compares it to that of the RF front-end. The measured NF for the microwave front-end is about 6 dB. By using the Friis equation for Noise Factor, $F = F_1 + (F_2 - 1)/G_1 + \dots$, where F_1 is the noise factor of the front end and F_2 is that of the photonic link, and then the result that $F \approx F_1$ indicates that $F_2 \approx 1$. Using the definition $F = SNR_i/SNR_o$, shows that the optical link does not add significant noise and that the noise figure of the system is largely set by the front-end, as expected.

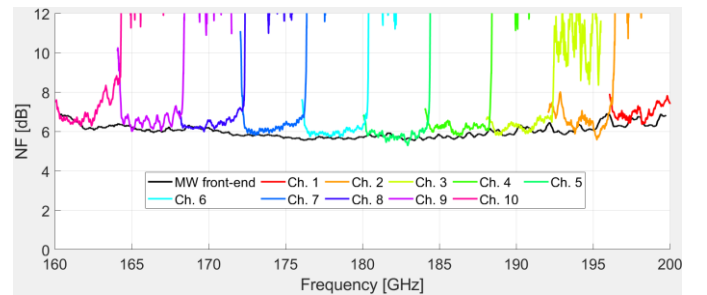


Fig. 7. Noise Figure of each individual SAWG output channel. Results demonstrate that the photonic link does not significantly add to the system noise.

Fig. 8 shows the NF of both the MW front-end and one of channels of the photonic link. The measured NF for the microwave front-end alone is 6 dB. The SAWG filter bandwidth is 2.2 GHz. The relative position between the lead and follower lasers can be controlled to $4 \text{ GHz} \pm 1 \text{ GHz}$. The NF increase after 2 GHz is due

to a combination of the filter cutoff frequency and the relative position of the follower laser tone. The results show that HyMPI enables hyperspectral resolution sounding without significantly increasing the system noise.

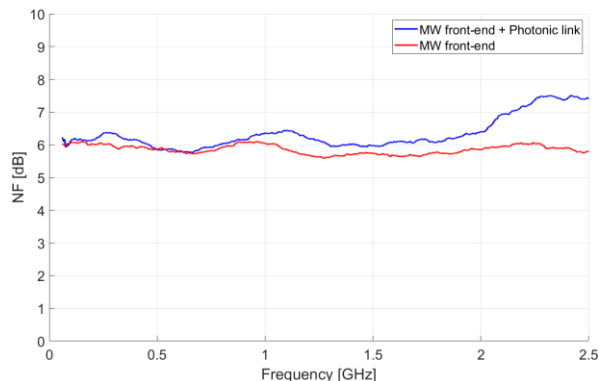


Fig. 8. Comparison of the measured noise figures of the RF receiver alone and with the photonic link. The NF increase near the 2.2 GHz region is a result of filter cutoff frequency and follower laser relative position.

V. CONCLUSION

The work presented the noise figure of an innovative microwave photonic instrument using photonic integrated circuit technology configured for hyperspectral detection of a 40 GHz spectrum. Our experiments demonstrated the instrument's capability of enabling wide-band, hyperspectral resolution and contiguous spectral coverage. We performed end-to-end system noise figure measurements and showed that the photonic link does not significantly impact system sensitivity. The use of a SAWG PIC provides considerable savings in size, weight, power consumption and cost. Future work will extend the sensitivity analysis to the superspectral detection of 40 GHz spectra and to hyperspectral detection that incorporates the spectrometer ASIC into the system. We will continue to investigate advancements in device development such as high capacity (>40 GHz) EOMs, integrated coherent receivers, integrated frequency combs, and others as we refine the instrument concept.

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