Ultra-Wideband RF-Photonics Technology for Microwave Spectrometry

Janusz Murakowski, Amjed Hallak, Andrew Mercante, Mathew J. Zablocki, Timothy Creazzo, Shouyuan Shi, Kevin Shreve, Matthew Gallion, Connor Creavin, Charles E. Harrity, Michael Gehl, Mehmet Ogut, Shannon T. Brown, Sidharth Misra, *Senior Member, IEEE*, Pekka Kangaslahti, Eric Kittlaus, *Member, IEEE*, and Dennis W. Prather, *Fellow, IEEE*

***Abstract*—We describe an RF-photonic system architecture to measure microwave spectrum over a wide bandwidth with high resolution. The approach relies on the up-conversion of the electronic signal to the optical domain using a high-speed electro-optic modulator, and an arrayed-waveguide grating (AWG) for spectral analysis. The modulator is implemented in lithium niobate whereas the AWG takes the form of a photonic integrated circuit fabricated in a silicon-on-insulator material platform. We present experimental results showing high-frequency response, in excess of 200 GHz, for the modulator, and broadband response of the AWG with the free spectral range of 81 GHz. The system is suitable for the measurement of atmospheric radiation between the oxygen and water vapor absorption lines for the monitoring of the planetary boundary layer to aid in weather prediction and the modeling of climate dynamics.**

***Index Terms*—Broadband receiver, microwave spectroradiometer, planetary boundary layer (PBL), radio frequency (RF) spectrometer, RF-photonics.**

I. Introduction

MOST of the Earth's energy exchange occurs within the planetary boundary layer (PBL). However, PBL is notoriously difficult to observe using traditional remote sensing techniques [1]. The key to PBL characterization is maximizing spectral information to enable accurate atmospheric retrievals near the PBL. For a space-based microwave radiometry application, narrow channel widths over a wide bandwidth are desired in order to measure the upwelling microwave radiance of the sky over varying PBL depths and shapes. Channel widths of 1 GHz or less, covering 40–50 GHz bandwidth, are desirable in order to achieve adequate altitude resolution of microwave sounders.

Received 30 April 2024; revised 1 July 2024 and 2 August 2024; accepted 17 August 2024. Date of publication 29 August 2024; date of current version 18 September 2024. This work was supported in part by NASA, 20-ACT20-0062, under Contract 80NSSC-21-K-0618, in part by the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration (80NM0018D0004), and in part by the National Technology & Engineering Solutions of Sandia, LLC under Contract DE-NA0003525 with the U.S. Department of Energy (DOE). *(Corresponding author: Janusz Murakowski.)*

Janusz Murakowski, Mathew J. Zablocki, Timothy Creazzo, Kevin Shreve, and Charles E. Harrity are with the Phase Sensitive Innovations, Inc., Newark, DE 19713 USA (e-mail: jam@udel.edu).

Amjed Hallak was with Phase Sensitive Innovations, Inc., Newark, DE 19713 USA. He is now with Textron Systems, Cockeysville, MD 121030 USA.

Shouyuan Shi and Dennis W. Prather are with the Phase Sensitive Innovations, Inc., Newark, DE 19713 USA, and also with the Electrical and Computer Engineering, University of Delaware, Newark, DE 19716 USA.

Matthew Gallion was with Phase Sensitive Innovations, Inc., Newark, DE 19713 USA. He is now with Hologic, Inc., Newark, DE 19702 USA.

Michael Gehl is with the Sandia National Laboratories, Albuquerque, NM 87123 USA.

Mehmet Ogut, Shannon T. Brown, Sidharth Misra, Pekka Kangaslahti, and Eric Kittlaus are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA.

Digital Object Identifier 10.1109/JSTARS.2024.3452033

Current state-of-the-art microwave radiometers typically rely on heterodyne receivers and digital spectrometers for atmospheric sensing. These systems, such as the Advanced Technology Microwave Sounder (ATMS) or the Microwave Humidity Sounder (MHS), operate across various frequency bands with channel widths ranging from several MHz to a few GHz, depending on the specific application and required resolution. See also [2], [3], [4], and [5] for state-of-the-art and recent developments in radiometer technology. However, conventional radiometers are typically narrowband, generally centered around the strong atmospheric absorption lines of oxygen and water vapor. While effective for certain atmospheric retrievals, these systems face limitations in spectral coverage and resolution adequate for the measurement of upwelling microwave radiance over the wings of the absorption lines, where crucial information about the PBL is encoded.

Here, we are developing a radio-frequency (RF) spectrometer that targets the bandwidth $\sim$140–190 GHz with 1 GHz resolution. The spectrometer relies on the up-conversion of captured radio frequency (RF) radiation to the optical domain using a high-speed electro-optic modulator (EOM) followed by an optical arrayed-waveguide grating (AWG) that analyzes the spectrum of the resulting optical modulation sideband [6], [7]. Broadband operation of the EOM enables faithful shifting of the RF spectrum to the optical domain where the high spectral resolving power of the AWG enables accurate sampling and wideband operation for high retrieval accuracy across the temperature and humidity sounding bands, and the ability to spectrally resolve the shape and magnitude of the sounding channel lines. The AWG is implemented as a silicon-based photonic integrated circuit (PIC) the size of a fingernail, whereas the core of the EOM is a 1-by-20 mm lithium-niobate chip. With the spectrometer's functionality obtained in such a tiny footprint, the complete system is amenable to the integration in a small, lightweight package suitable for deployment in space.

II. System Concept

Conventional microwave systems rely on the down-conversion of received signals to intermediate frequency (IF) for processing. To this end, the output of an electronic local oscillator is mixed with the signal of interest on a nonlinear element. The result is a combination of sum and difference frequency signals, of which the sum is spectrally filtered out, and the difference-frequency signal constitutes the IF, which contains all the information of the original microwave signal. The ultra-wideband spectrometer considered here performs a similar mixing of the incoming microwave with a local-oscillator output, except that the later lies in the optical portion of the electromagnetic spectrum. In other words, we up-convert the incoming microwaves to the optical domain by mixing them with a laser beam [8], [9], [10], [11], [12].

The nonlinear element used in the mixing process is an EOM that relies on the second-order nonlinearity of a crystal, such as lithium niobate (LNB), with a chemical formula $LiNbO_3$, for modulation. In LNB, the application of an external electric field modifies the refractive index of the material. As a result, the time-varying microwave signal applied to the crystal imposes phase modulation on the laser beam traversing it.

In the frequency domain, phase modulation manifests as the presence of modulation sidebands that flank the optical carrier—the original optical beam entering the crystal. For example, if the modulating signal is a single RF tone at frequency Ω and amplitude V, the complex amplitude of the phase-modulated optical beam may be expressed as

$$\begin{aligned} A\exp\left[j\left(\omega t+\pi\frac{V}{V_\pi}\sin(\Omega t)\right)\right] &= A\exp(j\omega t) \\ &+\pi\frac{AV}{2V_\pi}\exp\left[j(\omega+\Omega)t\right]+\pi\frac{AV}{2V_\pi}\exp\left[j(\omega-\Omega)t\right] \\ &+O(V/V_\pi)^2 \end{aligned} \tag{1}$$

where A is the amplitude of the optical signal and ω is its frequency, V_π is the modulator's half-wave voltage, and $O(V/V_\pi)^2$ indicates the presence of higher order terms that may be ignored for a small modulation index. On the right-hand side of (1), the first term represents the optical carrier whereas the second and third terms are the upper and lower sidebands, respectively, which are offset from the carrier's frequency ω by the RF frequency Ω.

Note that each of the sidebands contain all the information present in the original microwave signal, including the amplitude, phase, and frequency—just as in a conventional, purely electronic system. The difference is that now the RF is shifted to the optical domain, where the frequency is of the order of 200 THz.

Fig. 1 shows conceptually the approach to photonic processing of RF signals as contrasted with its electronic counterpart. Therein, Fig. 1(a) shows the conventional electronic processing of RF signals, whereas Fig. 1(b) shows the approach relying on photonic up-conversion.

The RF signal up-converted to the optical domain occupies a small fractional bandwidth compared to the carrier for even a very broad-band signal of interest. For example, 50 GHz, which is targeted in the present system, represents only 0.025% fractional bandwidth when mixed with a 200 THz near-infrared optical carrier. Such a narrow band generally simplifies signal processing. In addition, thin, flexible, lightweight, and low-loss optical fibers may be used for signal transmission, which enables back-end architectural flexibility. Finally, signal processing may be performed in the optical domain using small and lightweight PICs that further enable minimizing overall system size weight and power requirement envelope.

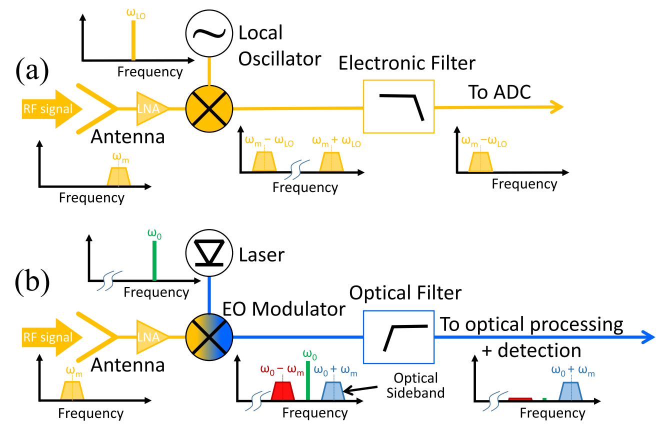


Fig. 1. (a) Conventional RF receivers down-convert the received signal using a mixer and local oscillator. (b) Optical receiver up-converts the received signal to optical domain using electro-optic phase modulator. An optical filter passes one sideband, which contains all the information carried by the RF signal.

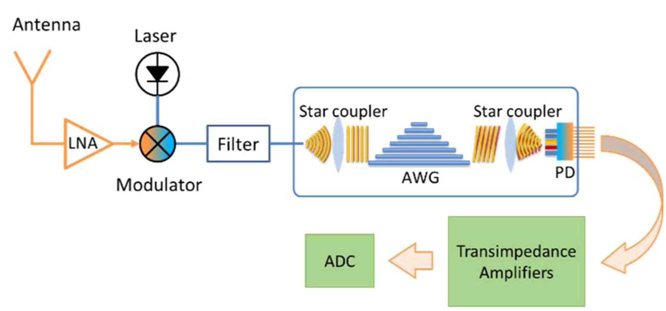


Fig. 2. Schematic diagram of the ultra-wideband RF-photonic spectrometer. LNA = low-noise amplifier; AWG = arrayed-waveguide grating; PD = photo diodes; ADC = analog-to digital converters. Star coupler in integrated optics plays the role of a lens in free-space optics [13], [14], [15].

To recover the signal spectrum, the optical modulation sideband, see Fig. 1(b), is conveyed to an AWG PIC, see Fig. 2. As the name implies, the latter includes an array of waveguides of varying lengths that introduce chromatic dispersion to the propagation of light. The waveguide lengths increment linearly from the shortest to the longest so that when light is evenly divided at their inputs, the optical phase at the outputs varies linearly across the array, and the slope of the phase front is a function of the input-light frequency or wavelength. An output star coupler converts the phase front to a focused spot, whose location depends on the phase-front slope and ultimately on the optical frequency of the input. This way, the AWG separates the

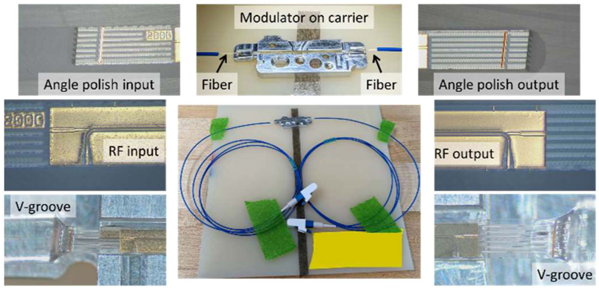


Fig. 3. Lithium-niobate electro-optic modulator packaged and ready for testing its frequency response.

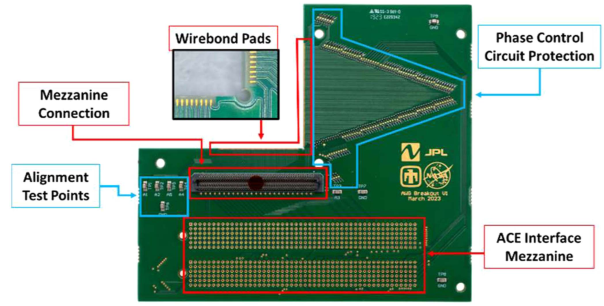


Fig. 4. AWG breakout printed circuit board.

different spectral components of incoming light, i.e., it acts as a spectrometer.

The power of light at the AWG outputs is detected by photodiodes (PDs) monolithically integrated on the PIC, amplified, and digitized using analog-to-digital converters (ADCs). Note that since the PDs act as integrated-power detectors, their frequency response needs to be only high enough to follow the changes in the sensed spectrum, i.e., they do not need to respond at 200 GHz of the incoming radiation or even at 1 GHz of the spectral resolution. Rather, we estimate a 10 ms response time, or $\sim$100 Hz bandwidth, to be adequate for the considered application. Fig. 2 shows schematically a conceptual diagram of the ultra-wideband RF-photonic spectrometer.

III. System Implementation

The conceptual simplicity of the system, as shown in Section II, lends itself to seemingly straightforward implementation. However, there are several complications that have to be taken into account to realize the potential benefits and deliver the sensitivity, latency, and update rate to make the spectrometer a practical system for the measurement of atmospheric radiation in the PBL.

First, the frequency of interest for PBL sensing reaches as far as 200 GHz. Therefore, both the RF front-end, which includes the antenna and the low-noise amplifier (LNA), and the EOM must operate up to such frequencies and produce a sizable sideband suitable for subsequent measurement by the AWG. EOMs operating at or above these frequencies have been previously demonstrated in a laboratory setting [10], [11]. Here, we further develop their packaging to make the EOMs suitable for field deployment. Fig. 3 shows an EOM chip package for testing high-frequency response. The test package includes both the mechanical support in the form of a carrier machined in aluminum, and the connection to the optical fiber for the input and output, where a V-groove is employed. In this test, the electrical connection is made using a high-frequency ground-signal-ground probe.

Second, for the spectrometer to be useful in PBL sensing, the spectral resolution should be 1 GHz or better over a broad frequency range covering at least 40–50 GHz between the atmospheric absorption lines around 119 and 183 GHz. Such a resolution entails a maximum delay difference between the AWG longest and the shortest waveguide of 1 ns or longer. When patterned in silicon having refractive index about 3.4 at the wavelength 1550 nm, this delay translates to about 8.8 cm long waveguide. Multiple such waveguides are patterned in a small footprint to take advantage of the microfabrication technology developed by the semiconductor industry over the past several decades. For the spectrometer discussed here, we chose 127 waveguides with a total length of about seven meters packed into a footprint less than 2 cm^2, which is a record-breaking device of this type [15], [16], [17], [18], [19], [20].

The large length of waveguides patterned in the AWG PIC introduces another complication, namely the potential variation of waveguide length due to fabrication tolerances and environmental perturbations such as temperature drift. For example, we estimate that the temperature change of 1 K would induce 10 GHz shift in the observed spectrum due to the thermo-optic effect in silicon. To compensate for these variations, an optical-phase-adjustment segment has been included in each of the 127 waveguides. While in principle two options for phase shifting in silicon waveguides are available, thermal and carrier-depletion, we chose the latter to avoid dissipating power in the PIC that may compromise its thermal stability—the very issue targeted by the phase adjustment. Thus, each waveguide included a segment of a PIN diode, the reverse biasing of which modifies the optical phase delay. The length of the PIN diode segment was chosen 2 mm to provide for a full 2π shift with a bias voltage below 8 V. Successful algorithms for AWG phase alignment have been developed in previous work [15].

As a result, the operation of the AWG PIC relies on making a single optical connection delivering the signal for analysis and multiple electrical connections for collecting the electronic outputs from the integrated PDs (51) and adjusting the phases in the waveguides (127). To access these control points, we developed a custom electronic system that interfaces with the AWG PIC. Fig. 4 shows the AWG breakout printed circuit board that interfaces directly with the AWG. Specific components are called out. For example, the wirebond pads are used to make electrical connections to the AWG PIC, whereas phase control circuit protection includes elements to prevent overvoltage from reaching the AWG internal circuitry that might otherwise damage the phase-adjustment PIN diodes. Fig. 5 shows the control-electronic board that on the one hand interfaced with the AWG, via the breakout board, and on the other with a general-purpose computer running software controlling the system. Accordingly, it contains ADCs to read the photocurrents, digital-to-analog

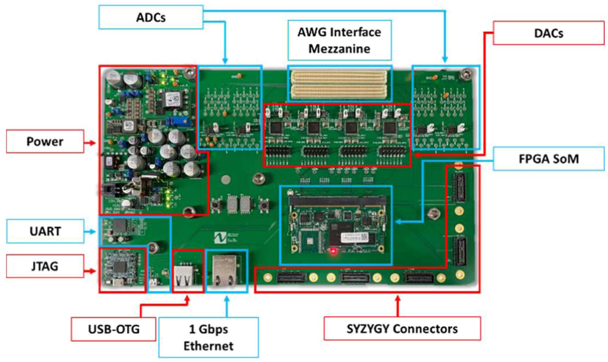


Fig. 5. AWG control-electronics board (ACE board).

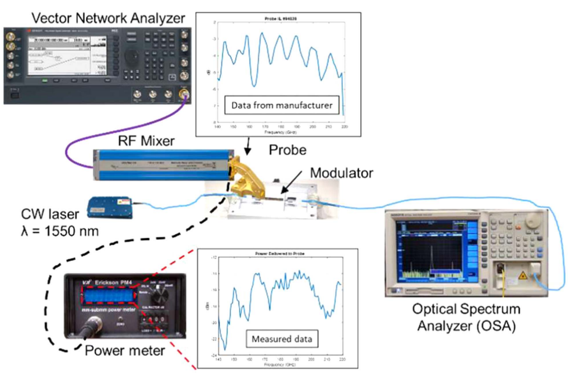


Fig. 6. Experimental setup for testing the high-frequency electro-optic modulator.

converters to apply voltages that set the optical-phase adjustment, field-programmable gate array system on a module to control the system in real time, and a variety of additional auxiliary components and interfaces.

IV. Component Testing

Before assembling the entire system, the individual components have been tested to verify that they meet the specifications needed for the envisioned application. Below, details on the testing procedures and results are presented.

A. Electro-Optic Modulator

The high-speed operation of the EOM was tested using an RF source and a 12x mixer to bring the frequency to the desired range, see Fig. 6. A computer, not shown, controls the experiment and collects measurement results. It is connected via a universal serial bus to the RF source in the form of a vector network analyzer and to the optical spectrum analyzer (OSA). The output of the RF source feeds a 12x mixer that is mounted on a micro-positioner stage for a fine control of the RF probe position. The latter is connected to the mixer via three rigid segments of a rectangular waveguide. The device under test—the electro-optic modulator, in this case—is attached to another micro-positioner stage for controlled movement, and is placed under an optical microscope utilizing long-working-distance objective lenses for viewing the contact area. Such an arrangement facilitates making a proper electrical contact between the high-frequency probe and the input pads of the co-planar waveguide in the electro-optic modulator. A power meter is used to measure the RF power at the output of the 12$\times$ mixer.

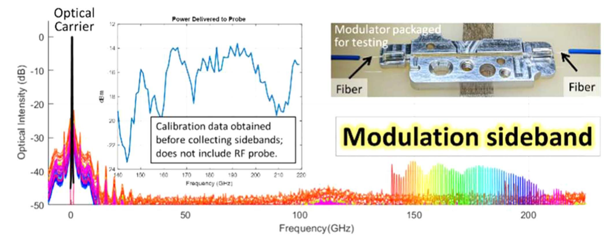


Fig. 7. Measurement of high-sped-modulator performance. Inset shows calibration data captured at the last connection to the probe. The sideband level is normalized to the measured input values.

Fig. 7 shows the optical spectrum gathered at the modulator output using the OSA when the modulator input is fed a high-frequency RF signal—one frequency at a time. To obtain the response of the modulator, the input amplitude is first measured at the last connection point before the RF probe so as to calibrate the output to the known value of the input. The inset of Fig. 7 shows the input signal measured at the last waveguide connection point (compare Fig. 6) immediately before the sideband data were collected by the OSA. The resulting optical spectra do not account for additional loss and residual variations due to a nontrivial spectral response of the probe itself. However, based on our prior experience, we estimate an additional $\sim$4 dB loss in the RF probe and the variation within 2–3 dB.

The rainbow-colored modulation sideband in Fig. 7 shows a significant (above the measurement noise floor) response of the modulator to frequencies between the low-frequency waveguide cutoff at 140 GHz and >200 GHz at the high end. The modulation efficiency may be extracted from the measured sideband power of about -38 to -41 dB relative to the optical carrier, which is normalized to the probe-input power shown in the inset. Taking into account the anticipated loss in the RF probe of $\sim$4 dB, the modulation efficiency within this frequency range is between -34 and -37 dB-m, which translates 0.2 to 0.4 W^{-1} on a linear scale, or V_π between 25 and 35 V assuming 50 Ω load, and is consistent with the anticipated values for the overall performance of the spectrometer. We estimate that this modulation efficiency, combined with the anticipated LNA gain and its maximum linear power output, is sufficient to generate a sideband that can be analyzed and detected by the AWG described below.

B. Arrayed-Waveguide Grating

For testing the quality of fabricated waveguides on the AWG PIC, a wafer was pulled out from the fabrication process before completing active components and depositing the metal layer. Accordingly, these samples contained no germanium for the PDs or doping for the phase adjustment. As such, they are not suitable for the final spectrometer, but may be used to verify the AWG design and its optical quality in terms of the waveguide length and loss. Fig. 8 shows an image of one die ready for optical testing.

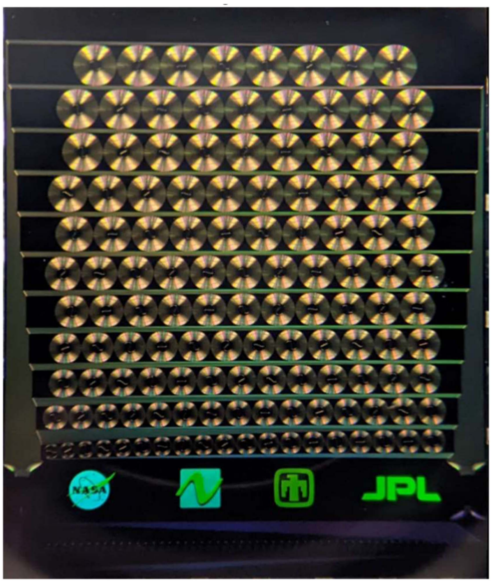


Fig. 8. Fabricated passive AWG chip.

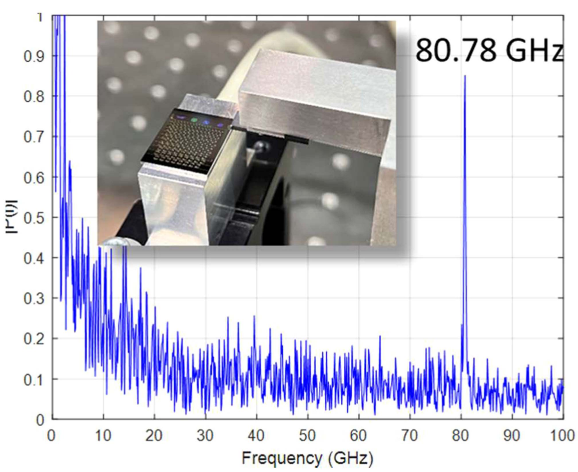


Fig. 9. Free-spectral-range measurement of the AWG using an OBR.

The passive AWG chip has been tested using an optical backscatter reflectometer (OBR), Luna 6415 from Luna Innovations. For the measurement, we used a polarization-maintaining fiber to couple the OBR with the AWG chip, as shown in the inset of Fig. 9. The OBR scan results were then Fourier transformed to convert the time domain to frequency domain. Fig. 9 shows the results of this experiment showing the Fourier transform of the OBR data with a prominent narrow peak at the free spectral range (FSR) of the AWG; the inset is a photograph of the measurement setup illustrating the placement of the AWG chip. Since FSR is the reciprocal of the shortest delay difference between adjacent waveguides of the AWG, the presence of the narrow peak indicates high accuracy of the waveguide lengths in the AWG per design specifications, as inconsistent delay differences would have broadened the peak. The FSR measured with the OBR is consistent with the AWG design.

V. Summary

We introduced a system architecture suitable for broadband, high-resolution spectrometry of microwave signals. The approach is suitable for sensing the atmospheric radiation in the wings of oxygen and water-vapor absorption lines and as such may aid in the sensing of PBL for weather forecasting, climate monitoring, and the development of models for atmosphere dynamics. The preliminary experimental results show that important performance metrics were met, including the high-frequency response of the electro-optic modulator that is instrumental in the up-conversion of incoming microwave radiation to the optical domain for processing, and the spectral response of an AWG PIC specifically designed and fabricated for this purpose. The forthcoming development of the ultra-wideband RF-photonic spectrometer is expected to yield an instrument capable of resolving 50 GHz bandwidth at 1 GHz increments within a footprint, weight, and power consumption attractive for wide deployment, including in the Earth orbit and beyond.

Acknowledgment

The Sandia employee owns all right, title, and interest in and to the article and is solely responsible for its contents. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this article or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the https://www.energy.gov/doe-public-access-plan.

References

[1] "National academies decadal survey for earth science and applications from space (ESAS 17)," The National Academies of Science, Engineering, and Medicine, 2017.

[2] "Center for satellite applications and research - NOAA /NESDIS / STAR, " NOAA / NESDIS / STAR website. Accessed: Jun. 2024. [Online]. Available: https://www.star.nesdis.noaa.gov/star/index.php

[3] J. F. Munoz-Martin et al., "The microwave temperature and humidity profiler: Description and preliminary results," *Sensors*, vol. 23, no. 20, Jan. 2023, Art. no. 20, doi: 10.3390/s23208554.

[4] J. T. Johnson et al., "Real-time detection and filtering of radio frequency interference onboard a spaceborne microwave radiometer: The CubeRRT mission," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 13, pp. 1610–1624, 2020, doi: 10.1109/JSTARS.2020.2978016.

[5] S. Misra et al., "Development of an on-board wide-band processor for radio frequency interference detection and filtering," *IEEE Trans. Geosci. Remote Sens.*, vol. 57, no. 6, pp. 3191–3203, Jun. 2019, doi: 10.1109/TGRS.2018.2882306.

[6] T. Dillon, C. Schuetz, and D. Prather, "Frequency agile microwave radiometer, hyperspectral microwave radiometer and methods of operation," US10917178B2, Feb. 2021 Accessed: Jan. 11, 2023. [Online]. Available: https://patents.google.com/patent/US10917178B2/en?oq=10917178

[7] T. Dillon, C. Schuetz, and D. Prather, "Frequency agile microwave radiometer, hyperspectral microwave radiometer and methods of operation," US11405113B2, Aug. 2022 Accessed: Jan. 11, 2023. [Online]. Available: https://patents.google.com/patent/US11405113B2/en?oq=11405113

[8] C. J. Huang, C. A. Schuetz, R. Shireen, S. Shi, and D. W. Prather, "LiNbO3 optical modulator for MMW sensing and imaging," in *Passive Millimeter-Wave Imag. Technol. X*. Bellingham, WA: SPIE, May 2007, pp. 123–131, doi: 10.1117/12.718794.

[9] J. Macario, P. Yao, R. Shireen, C. A. Schuetz, S. Shi, and D. W. Prather, "Development of electro-optic phase modulator for 94 GHz imaging system," *J. Lightw. Technol.*, vol. 27, no. 24, pp. 5698–5703, Dec. 2009, doi: 10.1109/JLT.2009.2035641.

[10] J. Macario, C. A. Schuetz, P. Yao, S. Shi, and D. W. Prather, "Development and characterization of LiNbO3 electro-optic phase modulator at 220 GHz for millimeter-wave imaging system," in *Millimetre Wave THz Sensors Technol. IV*. Bellingham, WA: SPIE, Oct. 2011, pp. 96–102, doi: 10.1117/12.898305.

[11] A. J. Mercante, S. Shi, P. Yao, L. Xie, R. M. Weikle, and D. W. Prather, "Thin film lithium niobate electro-optic modulator with terahertz operating bandwidth," *Opt. Exp.*, vol. 26, no. 11, pp. 14810–14816, May 2018, doi: 10.1364/OE.26.014810.

[12] D. W. Prather et al., "Millimeter-wave and sub-THz phased-array imaging systems based on electro-optic up-conversion and optical beamforming," *IEEE J. Sel. Topics Quantum Electron.*, vol. 29, no. 5, Sep. 2023, Art. no. 8501014, doi: 10.1109/JSTQE.2023.3306953.

[13] C. Dragone, "Efficient N X N star couplers using Fourier optics," *J. Lightw. Technol.*, vol. 7, no. 3, pp. 479–489, Mar. 1989.

[14] C. Dragone, C. H. Henry, I. P. Kaminow, and R. C. Kistler, "Efficient multichannel integrated optics star coupler on silicon," *IEEE Photon. Technol. Lett.*, vol. 1, no. 8, pp. 241–243, Aug. 1989, doi: 10.1109/68.36055.

[15] M. Gehl, D. Trotter, A. Starbuck, A. Pomerene, A. L. Lentine, and C. DeRose, "Active phase correction of high resolution silicon photonic arrayed waveguide gratings," *Opt. Exp.*, vol. 25, no. 6, pp. 6320–6334, Mar. 2017, doi: 10.1364/OE.25.006320.

[16] K. Takada, M. Abe, T. Shibata, and K. Okamoto, "1-GHz-spaced 16-channel arrayed-waveguide grating for a wavelength reference standard in DWDM network systems," *J. Lightw. Technol.*, vol. 20, no. 5, pp. 850–853, May 2002, doi: 10.1109/JLT.2002.1007939.

[17] Y. Hida et al., "400-channel 25-GHz spacing arrayed-waveguide grating covering a full range of C- and L-bands," in *Proc. Opt. Fiber Commun. Conf. Exhibit. Tech. Dig. Postconf. Ed. (IEEE Cat. 01CH37171)*, Mar. 2001, pp. WB2–WB2, doi: 10.1109/OFC.2001.928320.

[18] S. Cheung, T. Su, K. Okamoto, and S. J. B. Yoo, "Ultra-compact silicon photonic 512 $\times$ 512 25 GHz arrayed waveguide grating router," *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 4, pp. 310–316, Jul. 2014, doi: 10.1109/JSTQE.2013.2295879.

[19] F. M. Soares et al., "Monolithic InP 100-channel \times 10-GHz device for optical arbitrary waveform generation," *IEEE Photon. J.*, vol. 3, no. 6, pp. 975–985, Dec. 2011, doi: 10.1109/JPHOT.2011.2170558.

[20] F. Gambini, R. Moreira, D. Robles, A. Gambacorta, and M. Stephen, "An ultra-compact, narrow-bandwidth, and high-density channel photonic integrated channelizer based on serial arrayed waveguide grating architecture," *J. Lightw. Technol.*, vol. 42, no. 8, pp. 2908–2916, Apr. 2024.

Janusz Murakowski received the first M.S. degree from A. Mickiewicz University, Poznan, Poland, in 1990, the second M.S. degree from the Imperial Colledge, London, U.K., in 1991, and the Ph.D. degree from the University of Delaware, Newark, DE, USA, in 1999, all in physics.

He is currently Senior Scientist with Phase Sensitive Innovations, Inc., Newark, DE, USA. Until 2022, he was also an Associate Research Professor with the Department of Electrical and Computer Engineering, University of Delaware. He holds 40 issued U.S. patents, several international patents, is an author or coauthor of several books and book chapters, and more than 100 of peer-reviewed journal and conference publications. His areas of expertise include electromagnetic science and engineering, micro- and nano-fabrication, as well as photonic and electro-optic system design and innovation in addition to photonic modeling, design, fabrication and characterization. His present research interests are primarily in RF/microwave photonics, including system design, electro-optic modulation, nonlinear optical processes, transmission, detection, and imaging.

Amjed Hallak received the B.S. degree in electrical engineering with a computer science minor from the University of Delaware, Newark, DE, USA, in 2019.

He is currently a Digital Design Engineer III, working with designing, integration, and testing of electronic systems involving FPGAs for ruggedized RF tools and aircraft test systems with Textron Systems, Cockeysville, MD, USA. He has previously maintained leadership in a modernization effort targeted to the University of Delaware's introductory digital design and FPGA course. He has optimized and integrated various electronic control systems for systems requiring high data rates and low latency processing for novel RF and RF photonic applications, including passive millimeter wave imaging systems. He has one patent corresponding to his work with scalable FPGA integration in RF photonic systems. His research interests include SoC integration, hardware, firmware, and software development.

Mr. Hallak became a Member of IEEE Eta Kappa Nu in 2018.

Andrew Mercante received the B.S. and Ph.D. degrees in electrical engineering from the University of Delaware, Newark, DE, USA, in 2013 and 2018, respectively.

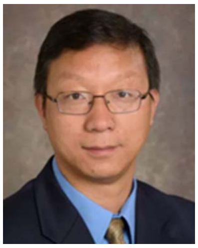
He completed a postdoctoral research with Phase Sensitive Innovations Inc., where his research interests included further development of thin-film lithium niobate devices and heterogeneous integration of materials. His focus was on the design and fabrication of ultra-wideband electro-optic phase modulators in thin-film lithium niobate.

Mathew J. Zablocki received the B.S. degree in physics with West Chester University, West Chester, PA, USA in 2007, and the Ph.D. degree in electrical engineering with the University of Delaware, Newark, DE, USA in 2012.

He is Director of Photonic Applications with Phase Sensitive Innovations, Inc., Newark, DE. He was Primary Investigator on two SBIR Phase II efforts and contributed to several SBIR/STTR efforts. His work continues in increasing performance and the manufacturing readiness level of next-generation lithium niobate modulators. He has four patents for photonic devices, and authored and coauthored on 20+ publications. His major research interests include the development of silicon based optical interconnects and the transfer of photonic devices in thin films.

Timothy Creazzo received the Bachelor's degree in electrical engineering from the Catholic University of America, Washington, DC, USA, in 2005, the Ph.D. degree in electrical engineering from the University of Delaware, Newark, DE, USA, in 2010.

He is currently a Director of Integrated Photonics, Phase Sensitive Innovations, Inc., Newark, DE. He has author or coauthor 20 US Patents and several additional US Patent Applications as well as over 20 journal and conference publications. His research interests includes research, development, and demonstration of new technologies related to integrated photonic devices across multiple material platforms for applications in RF photonic systems.



Shouyuan Shi received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Xidian University, Xi'an, China, in 1991, 1994, and 1997, respectively.

He is currently a Research Professor with the Department of Electrical and Computer Engineering, University of Delaware, Newark, DE, USA. He is also a Consulting Engineer with Phase Sensitive Innovations, Inc., Newark. He has authored or a coauthored eight books and book chapters, and more than 380 peer refereed journal and conference publications. He holds more than 20 issued US patents. He is also an Active Reviewer for more than 20 international peer-reviewed journals in the research areas of optics and photonics, RF, electro-optics, and electromagnetics. His research interests include computational electromagnetics, micro-optics and nano-photonics, and RF-photonics technologies and applications, including ultra-wideband RF antennas, optically addressed phase arrays, ultra-wideband electro-optic devices and systems, and passive and active millimeter wave imaging systems.

Dr. Shi also served as the Topic Editor of *Photonic Devices and Materials*, the *Optical and Photonic Letters*, and an Editorial Board Member of Advanced Optics.

Kevin Shreve received the B.S. degree in industrial technology-nuclear science from the Louisiana State University, Baton Rouge, LA, USA, in 1986.

Since graduating, he has worked for 35 years in photovoltaics R&D, photovoltaics manufacturing and reliability, photovoltaic products development, optoelectronics and RF-photonics R&D, optoelectronics device fab, and RF device integration & packaging. He has worked with AstroPower, Inc., G.E Energy, Blue Square Energy, The University of Delaware, and Phase Sensitive Innovations, where he is currently employed since 2011 as an R&D Engineer focused on RF and optoelectronics devices integration and manufacturing. He has authored or coauthored more than 20 technical papers and is a native US citizen.

Matthew Gallion received the B.S. degree in electrical engineering from the University of Delaware, Newark, DE, USA, in 2017.

During his undergraduate career with the University of Delaware, he was with a Research Group studying radar and beamforming communication systems. During his time as Lead R&D Electrical Engineer with Phase Sensitive Innovations (PSI), Inc., Newark, DE, USA, he led a team of engineers in advanced PCB design and power system integration across several millimeter-wave imagers and communication systems. He holds IPC certifications in PCB design and acceptability of electronic assemblies. In 2024, he joined Hologic, Inc., developing new electrical test methods used during the manufacture of industry-leading medical imaging devices. He has a patent focusing on scalable, modular phase control of optical channels. His research interests include power distribution and digital control of devices from system-level to chip-scale integration.

Connor Creavin received the B.S. degree in computer engineering from the University of Delaware, Newark, DE, USA, in 2021.

In 2020, he joined Phase Sensitive Innovations, Newark, DE, USA, as an Embedded Systems Engineer where he worked on high-speed transceiver technologies and digital signal processing techniques for imaging applications. In 2024, he became a member of TTM Technologies, Farmingdale, NY, USA, where he currently designs and develops custom circuitry to support critical, high-speed, low-latency systems. His research interests include high-frequency electromagnetic signals, digital signal processing, and the miniaturization of electronics and electronic components.

Charles E. Harrity received the Bachelor's degree in physics from the University of Delaware Newark, DE, USA, in 2009.

He is currently with Phase Sensitive Innovations, Inc., Newark. During his time at PSI, he has researched and developed mmW imaging systems to improve system performance and manufacturability and has been named principal investigator on several projects. He currently holds the position of Assistant Chief Technology Officer, leading the development of passive mmW imaging systems and RF Photonic Sources. He is co-author on over two dozen peer-reviewed journals and conference publications. His research interests include optical device packaging, mmW imaging, and mmW sensor manufacturing and design.

Michael Gehl received the Bachelor of Science degree in physics and optical engineering from Rose-Hulman Institute of Technology, Terre Haute, IN, USA, in 2009, and the Masters of Science degree in optical engineering and Ph.D. in optical engineering from the College of Optical Sciences, University of Arizona, Tucson AZ, in 2011 and 2015, respectively.

He completed post-doctoral work with Sandia National Laboratories, Albuquerque, NM, USA, from 2015 to 2017, exploring the optimization of arrayed waveguide gratings and the cryogenic operation of silicon photonic modulators. He continued as a Senior Member of Technical Staff with Sandia National Laboratories from 2017 to 2022 and a Principal Member of Technical Staff from 2022 to the present. His research interests include the design, fabrication and demonstration of novel integrated photonic components with application to photonic processing of RF signals and quantum information and sensing.

Mehmet Ogut received the B.S. degree in electrical and electronics engineering from the Bogazici University, Istanbul, Türkiye, in 2011, the M.S degree in electrical engineering from the George Washington University, Washington, DC, USA, in 2013, and the Ph.D. degree in electrical engineering from the Colorado State University, Fort Collins, CO, USA, in 2018.

He is currently working with NASA/Caltech Jet Propulsion Laboratory (JPL), Pasadena, CA, USA as a technologist in Microwave Instrument Science Group. He is the CO-I and JPL lead with Ultra-Wideband Photonic Spectrometer for Planetary Boundary Layer Sensing funded under NASA Earth Science Technology Office (ESTO) Advanced Component Technology (ACT-20), the CO-I of Smart Ice Cloud Sensing high frequency radiometer (250–670 GHz), sounder (380 GHz), and radar (240 GHz) awarded under NASA ESTO IIP-19, the CO-I of Compact Fire Infrared Radiance Spectral Tracker (c-FIRST) funded by NASA ESTO IIP-21, the CO-I of the Ultra-Wide RF ACT-22 project. His reserch interests include design, testing, calibration, and analysis of microwave and millimeter-wave radar/radiometer instruments, developing innovative concepts in radiometry, artificial intelligence and photonic applications in remote sensing.

Dr. Ogut is the recipient of the 2023 best paper award from IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY and also received the NASA's Exceptional Bravery Medal in 2024 and NASA JPL's Voyager award in 2023. He is currently the chair of IEEE GRSS Young Professionals.

Shannon T. Brown received the B.S degree in meteorology from the Pennsylvania State University, University Park, PA, USA, the M.S. degree in atmospheric science and the Ph.D. in geoscience and remote sensing, in 2005, from the University of Michigan, Ann Arbor, MI, USA.

He is a principle technologist and supervisor of microwave instrument science group with the NASA Jet Propulsion Laboratory, Pasadena, CA, USA. He has been involved with the spaceborne Topex and Jason Microwave Radiometers, WindSat Polarimetric Radiometer and the Jason follow-on Advanced Microwave Radiometers on Jason-2/3, Sentinel-6 and SWOT. He is the instrument scientist for the NASA Juno Microwave Radiometer and Principal Investigator for the US Air Force Compact Ocean Wind Vector Radiometer instrument that is being deployed on the International Space Station. His research interests include microwave radiometer calibration and geophysical algorithm development for both passive and active sensors.

Sidharth Misra (Senior Member, IEEE) received the B.E degree in electronics and communication engineering from Gujarat University, Ahmedabad, India, in 2004, the M.S. degree in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA, in 2006, and the Ph.D. degree from the Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, in 2011.

He is currently a technologist with the NASA Jet Propulsion Laboratory, Pasadena, CA, USA. He joined JPL in 2011 as a member of the Microwave Systems Technology group. He was a Research Engineer with the Space Physics Research Laboratory, University of Michigan and a Research Assistant with the Danish National Space Center, Technical University of Denmark (DTU), Lyngby, Denmark. He was also with the Space Applications Center, Indian Space Research Organization, Ahmedabad, India. He was with the calibration team of the Aquarius radiometer, and was the instrument-scientist on the RACE mission. He was also the digital back-end lead for the NASA CubeRRT mission. He is currently with the science team of SMAP, as well as Ocean Vector Winds for the COWVR mission, and radiometer calibration team member for the Juno microwave radiometer. He was the instrument manager for the PALS airborne system. He is currently the Instrument scientist for the NASA EZIE mission. His research interests include radio frequency interference algorithm development and mitigation, microwave radiometer system development and calibration.

Dr. Misra is the recipient of the IGARSS 2006 Symposium Prize Paper Award, the 2009 IEEE-GRSS Mikio Takagi award, 2012 IEEE TGRS best reviewer award, JPL Charles Elachi Early Career Award in 2016, a NASA Early Career Award in 2017, NASA Technical Achievement Award in 2019, a JPL Lew Allen Award in 2020, and also seven NASA Group Achievement Awards. He is the current Vice President for the IEEE Geoscience and Remote Sensing Society and a former Associate Editor for the *GeoScience and Remote Sensing Letters*, and a current Guest Editor for the *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*.

Pekka Kangaslahti received the Ph.D degree in electrical engineering from the Aalto University, Espoo, Finland, in 1999.

He is Group Supervisor with Microwave Systems Technology Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. He was Cognizant Engineer for HRMR instrument on Sentinel-6 to measure error of the radar path delay over coastal regions for ocean topography, and Co-I and JPL lead on the 118–850 GHz CubeSat scale instrument TWICE for cloud ice measurements where he demonstrated lowest noise 200–400 GHz InP MMIC LNAs. He demonstrated record low noise InP monolithic millimeter wave integrated circuits (MMIC) amplifiers and receivers for 180 GHz frequency. He developed the 70 GHz MMICs and receivers for PLANCK LFI (Planck Scientist), 23 GHz receiver for Juno MWR, the Radar Altimeter for HUYGENS/CASSINI, and arrays of millimeter wave radiometers for CMB QU Imaging Experiment (QUIET) (40 and 90 GHz) as well as GeoSTAR (50 GHz and 183 GHz). His research interests include primarily in the field MMIC and MMIC components and instruments.

Eric Kittlaus (Member, IEEE) was born in California, USA, in 1991. He received the Ph.D. degree in applied physics from Yale University, New Haven, CT, USA, in 2018.

He is currently a Research Technologist with the Microdevices Laboratory, NASA's Jet Propulsion Laboratory, Pasadena, CA, USA, where he develops active photonic device technologies for space applications. His research interests include acousto- and electro-optic device design, modeling, and fabrication, microwave photonics for millimeter-wave signal generation and detection, low-noise lasers, and integrated photonic and phononic circuits.

Dennis W. Prather (Fellow, IEEE) received the B.S.E.E., M.S.E.E., and Ph.D. degrees from the University of Maryland, College Park, MD, USA, in 1989, 1993, and 1997, respectively.

He began his professional career by joining the US Navy in 1982 as an E-1, where he served until 2021 and retired at the rank of CAPT (O-6) as an Engineering Duty Officer.

He worked as a Senior Research Engineer with the Army Research Laboratory, where he performed research on both optical devices and architectures for information processing. In 1997, he joined the Department of Electrical and Computer Engineering, University of Delaware, Newark, DE, USA, where he is currently the College of Engineering Alumni Distinguished Professor. His research interests include both the theoretical and experimental aspects of RF-photonic elements and their integration into various systems for imaging, communications, and Radar.

Dr. Prather is an Endowed Professor of Electrical Engineering, a Fellow of National Academy of Inventors (NAI), Fellow of the Society of Photo-Instrumentation Engineers, and a Fellow of the Optica (formerly Optical Society of America).