A Compact 600 GHz Electronically Tunable Vector Measurement System for Submillimeter Wave Imaging

Robert J. Dengler, Frank Maiwald and Peter H. Siegel

Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA

***Abstract* — A compact submillimeter wave transmission/reflection measurement system has been demonstrated at 560-635 GHz, with electronic tuning over the entire band. Maximum dynamic range measured at a single frequency is 90 dB (60 dB typical), and phase noise is less than +/- 2°. By using a frequency steerable lens at the source output and mixer input, the frequency agility of the system can be used to scan the source and receive beams, resulting in near real-time imaging capability using only a single pixel.**

***Index Terms* — Submillimeter wave imaging, Submillimeter wave mixers, phase measurement.**

I. Introduction

Vector network analyzers (VNAs) have been used for decades for electrical characterization of transmission line components [1, 2] and bulk materials [3-5]. To date, swept VNAs are commercially available only up to 325 GHz with a dynamic range of 40 to 50 dB at the highest frequencies [6-8]. VNAs with higher frequency capability are available but utilize mechanically tuned Gunn oscillators and hence have very limited electronic tuning capability [9].

The instrument described here uses multiplied submillimeter-wave sources derived from low-cost microwave synthesizers. The phase reference is generated at low RF frequencies, reducing the amount of submillimeter wave hardware required. By judicious choice of IF frequencies, a significant amount of commercial off-the-shelf communications hardware could be utilized in the instrument, further reducing cost. The rapid frequency tuning capability of this system can be employed to provide fast image acquisition by using a dispersive lens designed to steer the transmit and receive beams in one dimension as a function of frequency. A complete image can then be acquired via frequency sweeping and mechanical scanning in only one dimension.

II. Measurement System

The vector measurement system uses X36 multiplication as the signal source and a subharmonically-pumped mixer (LO ≅ $f_{SIG}/2$) as the signal downconverter [10]. The signal and LO are derived from a pair of compact microwave synthesizer modules having a tuning range from 14 to 18 GHz and step size of 250 kHz. Both synthesizers are multiplied by a pair of Millitech X6 active multipliers. The resulting 100 GHz signals are then amplified by about 20 dB by a pair of MMIC power amplifiers [11, 12]. The amplified signal is then multiplied by X6 (signal) or X3 (LO) by a set of doublers and triplers developed for the Herschel Space Telescope instrument [13]. Both signal and LO synthesizers are controlled from a laptop PC via a 4 wire synchronous serial interface, using the PC parallel port and a custom driver written in Visual Basic. The frequencies of both synthesizers are adjusted so that a constant IF frequency of 450 MHz is generated at the IF output of the 600 GHz mixer.

To avoid the need for submillimeter hardware to produce the phase reference signal for the system, coupled output from the two synthesizers is mixed directly. The resulting 12.5 MHz sub-IF is then multiplied 36 times, the same factor as for the synthesizer outputs. The multiplier used is a transmitter exciter board extracted from a General Electric “Mastr Executive II” commercial two-way mobile transceiver. These surplus units are widely available for ~$100, while a custom-built X36 multiplier for the same frequency range would cost over $4,000. Since the exciter was originally designed to meet Federal Communications Commission spectral purity standards for transmitters in the Land Mobile Radio Service, the spurious level output from the multiplier (< -60 dBc) is far below what is required for the measurement system. The low-cost synthesizers used in this system have poor phase noise characteristics (-54 dBc/Hz @ +/- 1 kHz), and as a result the highly multiplied 450 MHz IF signals (both measurement and reference) are actually indiscernible from the accompanying phase noise when viewed on a spectrum analyzer at any resolution bandwidth. Therefore it is necessary to reference both the signal and reference IFs to a stable source before detection [14]. This is accomplished by shifting the 450 MHz reference 12.79 MHz down in frequency using a fundamental crystal oscillator, mixer and bandpass filter, and then mixing the resultant 437.21 MHz signal with the 450 MHz IF signal. Since the phase noises of the shifted 437.21 MHz and 450 MHz IF signals are totally correlated, mixing the two signals cancels out that noise, leaving a 12.79 MHz signal that has the same amplitude and phase characteristics (minus the synthesizer noise) as the 450 MHz IF signal.

It should be noted that any 450 MHz reference signal passing through the 437.21 MHz bandpass filter will be downconverted at the 450 MHz signal mixer, resulting in crosstalk and loss of dynamic range. It is therefore absolutely essential that the 437.21 MHz filter have extremely high rejection at 450 MHz. The chosen filter, a Motorola

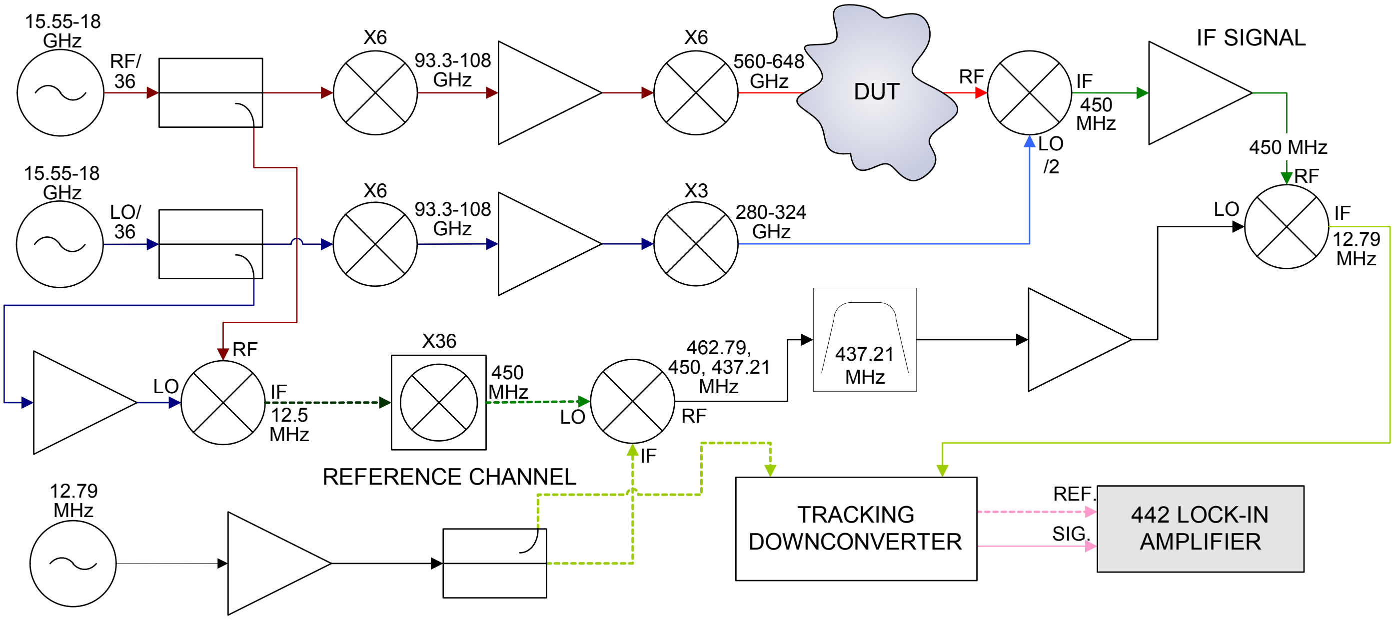

Fig. 1. Block diagram of measurement system.

TFE6213A (extracted from a Motorola "Micor" communications radio, price ~$5) is very small yet has over 100 dB of rejection at 450 MHz. The relatively high loss of this filter (10 dB, due to the small size vs. high Q) is easily compensated for by additional amplification.

The 12.79 MHz signal and reference channels are finally converted to ~66 kHz for detection by a Scitec model 442 lock-in amplifier using a 12.86 MHz oscillator, isolation amplifiers, couplers and mixers. The lock-in amplifier functions as a variable bandwidth magnitude and phase receiver. Bandwidth and gain are also controlled by a laptop PC via a 9 bit parallel interface, while the vector X and Y DC outputs of the lock-in amplifier are read by an analog data acquisition card in the PC and converted to polar format. At maximum detection bandwidth, real-time acquisition speeds of over 3000 points per second are possible.

III. Performance Tests

To test the performance of the instrument and verify accurate phase measurement capability, the relative phase delays of several bulk materials were measured over 31 frequencies from 560 to 635 GHz. This was done by first performing a simple transmission response calibration, measuring the magnitude and phase of the transmission path without the material at each frequency. By subtracting the calibration data from subsequent measurements, the additional phase introduced by inserting the device under test (DUT) between the submillimeter source and mixer could be measured. Figure 2 illustrates the phase stability of the system in the clear through measurement as well as the relative phase vs. frequency of a Teflon sample. An accurate

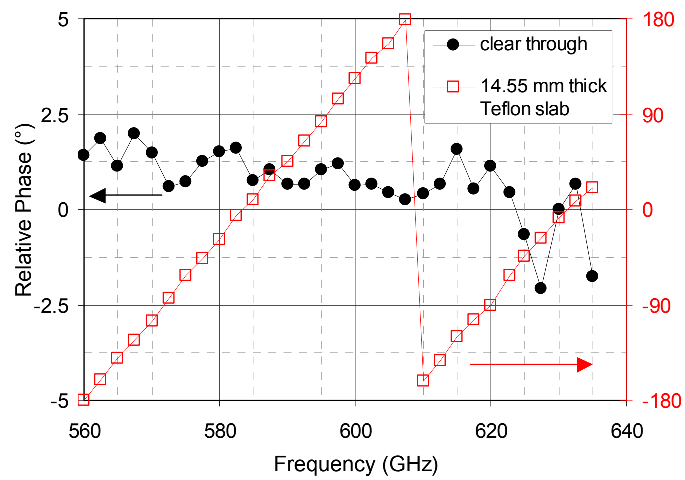

Fig. 2. Relative phase measurement with and without Teflon slab between source and mixer.

determination of the rate of change of phase with respect to frequency $\delta\phi/\delta f$, or time delay, was then obtained using

$$\varepsilon = \left(\frac{\partial \phi}{\partial f} \cdot \frac{c}{360 \cdot l} + 1 \right)^2 \tag{1}$$

where l is the physical length of the material slab and $\delta\phi/\delta f$ is the rate of phase change in degrees per Hertz. Table 1 contains a summary of the dielectric constant measurements of 6 bulk materials over 560-635 GHz, 3 which have well-known dielectric constants at submillimeter wavelengths [15]. The relatively good agreement between the measured dielectric constant and the values given in [15] indicate proper operation of the system. The small errors in dielectric constant are likely due to path length errors caused by errors in sample thickness measurement, and deviation from normality in the beam path within the sample.

TABLE I
BULK MATERIAL PHASE MEASUREMENT RESULTS

Material	Thickness (mm)	δφ/δ*f* (°/GHz)	Dielectric Constant	% error from [15]
Teflon	14.55	7.73	2.080	1.3
Polyethylene	25.1	16.35	2.379	2.4
TPX	11.4	6.36	2.144	0.6
Polypropylene	24.7	15.14	2.284	-
Aerogel	16.5	0.47	1.048	-
High-resistivity Si	1.00	2.96	12.03	-

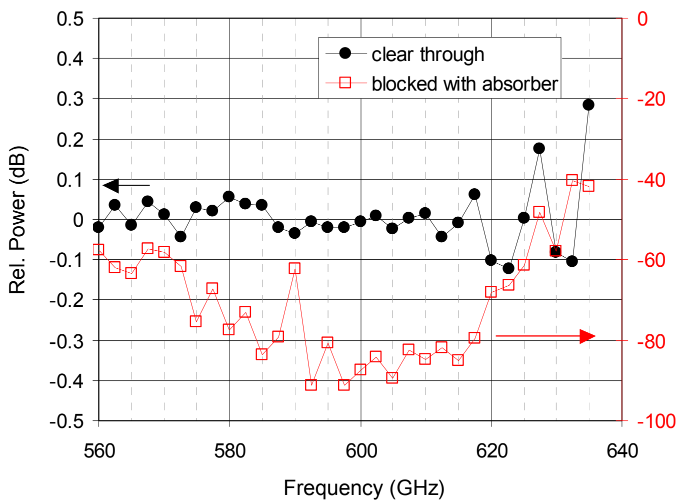

Fig. 3. System amplitude stability and dynamic range.

Figure 3 shows the amplitude stability and dynamic range of the system, the latter measured by placing absorber in the DUT path after calibration. Both stability and dynamic range are degraded above 625 GHz. In fact, even though the microwave synthesizers enabled the system to operate up to 648 GHz, stable measurements above 635 GHz were not possible. Although the mixer appeared to be well driven with LO power above 640 GHz as evidenced by observed change in the bias voltage, it is possible that a undesired harmonic from the LO multiplier chain was in fact driving the mixer. As a result, no 450 MHz signal would be present at the submillimeter mixer IF output despite adequate LO power because that power was at the wrong frequency. Improving the bandwidth of the multipliers such that the desired harmonic is at least equal in strength to the sum of the powers of the undesired harmonics should provide adequate operation.

IV. Future Work

The subharmonic mixer used in this system was designed for the Microwave Limb Sounder instrument aboard the Earth Observing System Aura satellite launched in 2004. Although designed for wide RF bandwidth, it was also optimized for use at only a single fixed LO frequency. Initially it was necessary to manually retune the mixer at each measurement frequency in order to couple enough LO power to drive the mixer into operation. By adding a 0.5 mA constant current bias path to the IF output circuit, it was possible to operate one of the two antiparallel mixer diodes at greatly reduced LO power, allowing totally automatic operation at the cost of degraded mixer performance. Clearly a modified mixer design that offers a wide LO bandwidth will yield superior performance.

In order for this single pixel measurement system to be usable for near real-time imaging (~1 frame per second), some form of electronic beam steering must be incorporated. One possible solution would be to raster scan the beam rapidly in one dimension using a frequency steerable lens [16] and slowly in the other dimension using a mechanical rotation stage. This would require frequency scanning at a rate of over 100 points per second. However, the low-cost synthesizers used in the current implementation have a switching speed of 100 milliseconds. In addition, adjustments to the 100 GHz power amplifier biases were required during frequency changes to protect the submillimeter wave multipliers from possible damage caused by power spikes. The power supplies used were not designed for high-speed operation, so considerable delay was added as a result of the multiplier protection routine. By replacing the synthesizers and power supplies with high-speed units, frequency stepping speeds could be improved from the current 5 frequencies per second to over 100 frequencies per second. Further improvements in performance may be obtained by developing more robust submillimeter multipliers that could withstand momentary input power surges without damage. This would allow the system to operate fully powered at all times, resulting in reduced thermal drift in the millimeter wave amplifiers.

V. Conclusion

A complete vector measurement system has been designed, constructed and tested over 560-635 GHz with a typical dynamic range of over 60 db and acquisition speed of over 3000 points per second at a single frequency. Through the addition of dispersive optics to the RF ports and use of faster synthesizers, the system will be well suited for near real-time active submillimeter wave imaging.

Acknowledgement

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space

Administration. The authors wish to acknowledge the assistance and support of Mr. John E. Oswald and Mr. Robert H. Lin who provided the 640 GHz heterodyne mixer, and Dr. John Pearson and Ms. Mary Soria for providing the MMIC power amplifiers.

REFERENCES

[1] R. A. Witte, *Spectrum and Network Measurements,* First Noble Publishing, 2001, pp. 236-283.

[2] A. D. Helfrick, *Electrical Spectrum and Network Analyzers,* Academic Press Inc., 1991, pp. 188-201.

[3] J. Ness, "Broad-Band Permittivity Measurements Using the Semi-Automatic Network Analyzer", *IEEE Trans. Microwave Theory & Tech.*, vol. 33, no. 11, pp. 1222-1226, November 1985.

[4] J. P. Grant, R. N. Clarke, G. T. Symm, N. M. Spyrou, "A critical study of the open-ended coaxial line sensor technique for RF and microwave complex permittivity measurements", *J. Phys. E: Sci. Instrum.,* vol. 22, pp. 757-770, 1989.

[5] W. B. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies", *Proc IEEE*, vol. 62, pp. 33-36, Jan. 1974.

[6] Agilent Technologies, 395 Page Mill Rd. Palo Alto, CA 94306.

[7] Anritsu Microwave Measurements Division, 490 Jarvis Dr. Morgan Hill, CA 95037.

[8] OML, Inc., 300 Digital Dr. Morgan Hill, CA 95037.

[9] AB Millimetre, 52 rue Lhomond, 75 005 Paris, France.

[10] I. Mehdi, P. Siegel, D. Humphrey, T. Lee, R. Dengler, J. Oswald, A. Pease, R. Lin, H. Eisele, R. Zimmermann, N. Erickson, "An All Solid-State 640 GHz Subharmonic Mixer," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 403-406, June 1998.

[11] L. Samoska, T. Gaier, A. Peralta, S. Weinreb, J. Bruston, I. Mehdi, Y.C. Chen, H.H. Liao, M. Nishimoto, R. Lai, H. Wang, Y.C. Leong, "MMIC Power Amplifiers as Local Oscillator Drivers for FIRST", *Proc. SPIE*, vol. 4013, pp. 275-284, 2000.

[12] H. Wang, L. Samoska, T. Gaier, A. Peralta, H.-H. Liao, Y.C. Leong, S. Weinreb, Y.C. Chen, M. Nishimoto, R. Lai, "Power-Amplifier Modules Covering 70-113 GHz Using MMICs," *IEEE Trans. Microwave Theory and Tech.*, vol. 49, pp. 9-16, 2001.

[13] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, C. Tripon-Canseliet, G. Chattopadhyay, I. Mehdi, "A 540-640-GHz High-Efficiency Four-Anode Frequency Tripler," *IEEE Trans. Microwave Theory and Tech.*, vol. 53, pp. 2835-2843, 2005.

[14] J. Doane, "Broadband superheterodyne tracking circuits for millimeter-wave measurements", *Rev. Sci. Instrum.*, vol. 51, pp. 317-322, 1980.

[15] J. R. Birch, J. D. Dromey, J. Lesurf, "The Optical Constants of Some Common Low Loss Polymers Between 4 and 40 cm^{-1}", *National Physical Laboratory Report DES 69*, February 1981.

[16] Goutam Chattopadhyay, private communication.