Improved 240-GHz Subharmonically Pumped Planar Schottky Diode Mixers for Space-Borne Applications

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***Abstract*—Low-noise broad intermediate frequency (IF) band 240-GHz subharmonically pumped planar Schottky diode mixers for space-borne radiometers have been developed and characterized. The planar GaAs Schottky diodes are fully integrated with the RF/IF filter circuitry via the quartz-substrate upside-down integrated device (QUID) process resulting in a robust and easily handled package. A best double-sideband-mixer noise temperature of 490 K was achieved with 3 mW of local-oscillator power at 2-GHz IF. Over an IF band of 1.5–10 GHz, the noise temperature is below 1000 K. This state-of-the-art performance is attributed to lower parasitic capacitance devices and a low-loss waveguide circuit. Device fabrication technology and the resulting RF mixer performance obtained in the 200–250-GHz frequency range will be described.**

***Index Terms*—Millimeter-wave receivers, mixer noise, mixers, Schottky diode mixers.**

I. Introduction

SINCE THE initial development and demonstration of the surface-channel-etched (SCE) diode structure by Bishop *et al*. [1], the planar GaAs Schottky diode chip has been widely deployed in millimeter-wave mixers and multipliers. Novel technologies for further reducing the parasitics continue to be explored [2], [3], but the most successful implementations are still based on the SCE diode structure. The demonstration of fundamental planar mixers [4], [5] led to the development of diode pairs on a single chip for subharmonic mixing applications [6]–[8]. These results were based upon discrete diode chips that were either soldered or bump bonded into the circuit. Mounting of the discrete planar diode chips was far easier than the traditional whisker-contacted devices. However, as the frequency of operation increased and the diode chip size decreased, chip handling and placement became difficult. At frequencies above 200 GHz, the GaAs substrate becomes a significant portion of a wavelength. In traditional waveguide designs, which place the diode across the signal guide, this GaAs substrate can significantly degrade performance. To circumvent these concerns and allow the planar devices to be used at much higher frequencies, a technique was developed to integrate the GaAs diodes with the physically larger surrounding microstrip filter circuitry, which is generally formed on lower-dielectric-constant lower-loss quartz. This technique, designated quartz-substrate upside-down integrated device (QUID) for QUID process, utilizes a heat-cure epoxy to bond the diode chip, with devices upside-down onto a quartz substrate [9], [10]. Discrete substrateless upside-up planar chips on quartz were demonstrated as early as 1990 [11]. Although the QUID technology was developed explicitly to enable the use of planar diodes in the 400–700-GHz range, where chip size is a limiting factor, its advantages at lower frequencies are apparent. Firstly, by combining the GaAs devices with the filter circuitry, the "chip" size is increased substantially, making handling easier. Secondly, all of the unnecessary high-dielectric constant semiconductor material is eliminated from the final structure improving circuit performance. This technology has enabled planar subharmonically pumped mixers (SHPM's) up to 600 GHz [12], [13]. In this paper, we report on a QUID-style 240-GHz SHPM, which is being developed for the NASA Earth observing system-microwave limb sounder (EOS-MLS) instrument, an ozone-depletion monitoring satellite to be launched early in the next century. The measured performance of these mixers is slightly better than the performance of discretely mounted chip diode mixers and the extra degree of circuit integration makes them more reliable and much easier to assemble in waveguide circuits. The successful implementation of this technology at 240 GHz has allowed us to scale directly to 650 GHz for similar space-borne applications.

QUID-style devices have now been fabricated both at the Jet Propulsion Laboratory (JPL), Pasadena, CA, and at the University of Virginia (UVa), Charlottesville, using distinct processing technologies. Section II details the two device processes. Section III discusses the improvements which have been made to the microstrip circuit and waveguide block to enhance mixer performance. Section IV summarizes the measured results which have been obtained to date.

Manuscript received November 20, 1997; revised June 16, 1998.

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Publisher Item Identifier S 0018-9480(98)09047-4.

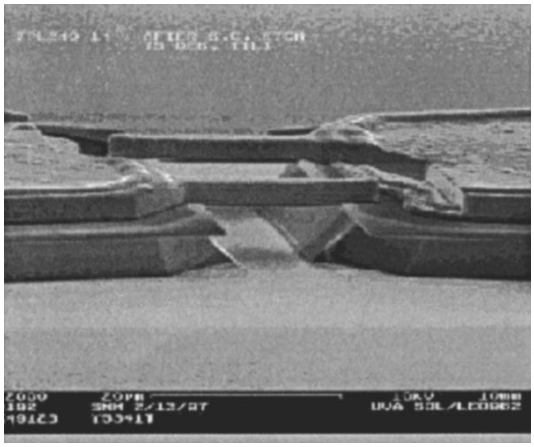


Fig. 1. SEM close-up of the anode region in a UVa device. This SEM was taken after the completion of the front-side process and before the QUID process.

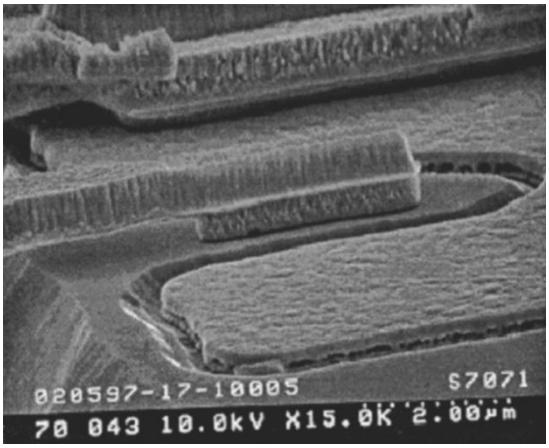
II. Device Processing

Devices fabricated at both the UVa and JPL have been tested in the same waveguide blocks. A complete discussion of the fabrication steps used in the UVa and JPL processes has been reported [12], [14], however, it is worthwhile to elaborate on the key differences between the two technologies.

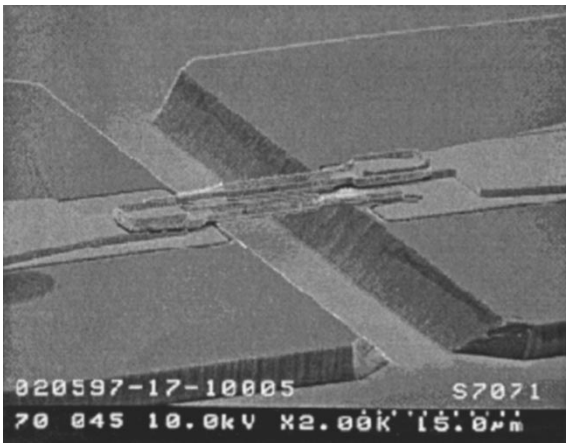
Perhaps the most important difference between the two device processes is the method used for forming the Schottky contact. The UVa anode is circular, made by a combination of dry and wet etching of the SiO_2 and then electroplating of Pt/Au. The finger is formed after the anode and is a combination of sputtered Cr/Au and electroplated Au. It is nominally 2.5-μm wide, tapering down to 1.75 μm at the anode, and 2.5-μm thick. This structure provides both a robust contact to the Schottky anode and increased mechanical rigidity due to the extra finger thickness. A scanning electron micrograph (SEM) of the finger/anode structure after the surface channel etch is shown in Fig. 1.

In comparison, an SEM picture of the JPL device (before QUID process) is shown in Fig. 2. The rectangular-strip anodes are made with a tri-level e-beam process that uses multiple scans at different doses to expose the footprint and separately expose the side beams of the T-structure. The technique provides the flexibility to arbitrarily define the size of the footprint and top-beam overhang. In this process, the finger is an integral part of the anode and is written at the same time. Schottky metal consists of Ti/Pt/Au (300/300/8000 Å). The nominal finger width is 2 μm over most of the airbridge and tapers down to 0.5 μm before contacting the anode. Fig. 2(a) shows a close-up of the T-anode geometry. The width of the anode is typically between 0.25–0.4 μm and the length can be as long as several microns, depending on the desired impedance.

Once the front-side processing is complete, the QUID process is utilized in which a two-part heat-cured epoxy is used to bond the GaAs substrate upside-down to a quartz-host substrate. In the JPL process, the substrate is removed to an AlGaAs etch stop layer in a selective GaAs wet etch. After the backside alignment, GaAs outside the device anode area is



(a)



(b)

Fig. 2. SEM pictures of the JPL devices. (a) Close-up of the T-anode. (b) Diode pair after channel etch and before the QUID process.

etched using a chlorine reactive ion etch (RIE) process. In the UVa process, the substrate is also removed to an AlGaAs etch stop with wet chemical etching, followed by a dry etch of the GaAs after backside patterning. The oxide is then removed in a CF_4 RIE plasma, and chrome sputter etching exposes the Au filter structures.

A. Device DC Characteristics

Tables I and II contain a sample set of the diodes fabricated both at JPL and UVa that have been tested. Device dc parameters for each diode are based on standard $I(V)$ and zero-bias capacitance measurements. The UVa diodes generally have a higher turn-on voltage. We believe this is due to the UVa anodes being electroplated rather than evaporated resulting in a superior metal–semiconductor contact.

An impedance meter with a coaxial probe is used to measure the total circuit capacitance at 1 MHz. Reference devices with short and open anodes and missing anode fingers are used to extract the device values. For both the UVa and the JPL diodes, the total capacitance of the structures ranges from 13 to 17 fF. Each anode has about 1.5–2 fF, while the remaining capacitance is attributable to the parasitic capacitance of the structure and filter circuit. The pad-to-pad capacitance

TABLE I
PHYSICAL PROPERTIES OF THE DIODES USED IN THIS STUDY. EPILAYER IS NOMINALLY 100 nm. THE TOP THREE AND BOTTOM TWO DIODES WERE FABRICATED AT THE JPL AND UVa, RESPECTIVELY

Diode	Doping (cm^{-3})	Area (μm^2)	Finger length (μm)
A-110196-14-9114-1	2.0×10^{17}	1.35	40
B-020597-18-10005-1	4.0×10^{17}	0.90	40
C-020597-18-10005-2	4.0×10^{17}	0.90	40
D-UVa-JPL240-15-D1	1.9×10^{17}	1.23	20
E-UVa-JPL240-13-B4	1.9×10^{17}	0.95	20

TABLE II
MEASURED CHARACTERISTICS OF THE DIODES USED IN THIS STUDY

Diode pair	η	R_s Ω	Is Amps	C_{tot}(fF) before etch	C_{tot}(fF) after etch
A	1.27 1.24	9 7	3.8×10^{-14} 3.8×10^{-14}	15.2	12.8
B	1.26 1.25	7 7	2.4×10^{-14} 2.0×10^{-14}	15.8	13.6
C	1.26 1.31	7 7	2.8×10^{-14} 7.1×10^{-14}	15.2	13.8
D	1.26 1.46	12 10	1.1×10^{-14} 4.6×10^{-14}	15.8	12.9
E	1.28 1.24	15 13	9.8×10^{-16} 2.3×10^{-16}	15.6	12.5

varies from 6 to 8 fF, while the pad-to-finger capacitance is approximately 1–2 fF. Finally, 3 fF of distributed capacitance falls to the large filter structure.

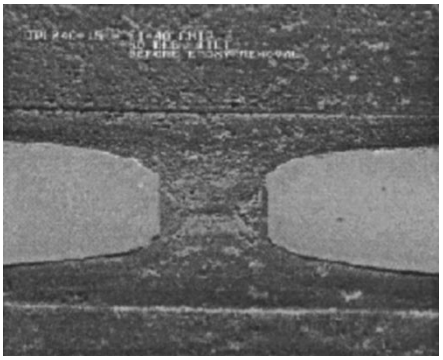
B. Parasitic Capacitance Reduction

Based on computer simulations which include the effect of parasitic capacitance on mixer performance [15], a reduction in pad-to-pad capacitance can result in improved performance if the finger inductance is in the optimum range. In the QUID structure, epoxy with a dielectric constant of 3.1 fills the usually air-filled surface channel increasing the pad-to-pad capacitance. Recent experiments conducted at UVa demonstrated that the epoxy could be etched away in an oxygen plasma, reducing the pad-to-pad parasitic capacitance substantially [14]. Fig. 3 shows a UVa-style device before and after this epoxy etch step. Results for several devices are given in Table II. In general, the pad-to-pad capacitance is reduced by as much as 30%, from 6–8 to 4–6 fF. The effect of this reduction on mixer performance will be presented in Section IV.

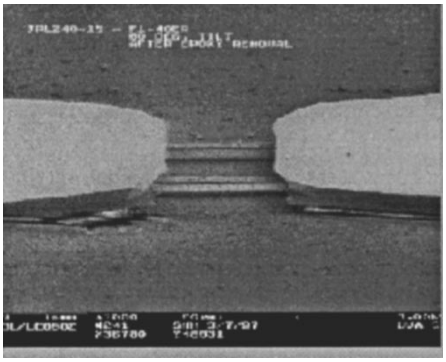
III. MIXER BLOCK

A. Microstrip Filter Circuit

The microstrip filter circuit, part of the QUID structure, consists of hammerhead filter sections on each side of the diode pair. The design of the filter is identical to [7] with some minor modifications. The initial 50-Ω matching section on the intermediate frequency (IF) side has been empirically optimized for maximum local oscillator (LO) coupling. The IF pass LO/RF reject filter now consists of two long hammerhead sections (for LO rejection) plus a short hammerhead section (for signal rejection). Operation of the filter was confirmed



(a)



(b)

Fig. 3. SEM photo of a QUID device (a) before and (b) after the epoxy has been etched in an oxygen plasma.

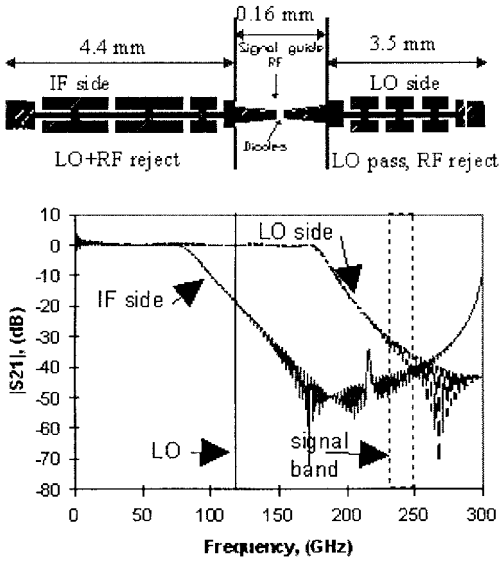


Fig. 4. FDTD computer simulation of the microstrip filter used with the subharmonic mixer. For more details on the simulation procedure, see [16].

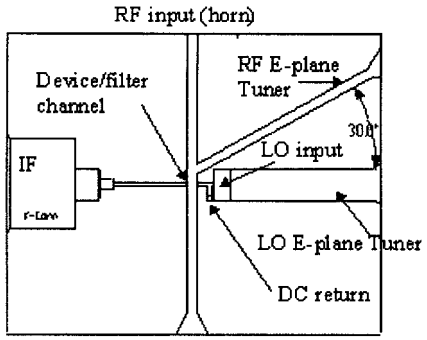


Fig. 5. Drawing showing the lower half of the waveguid-mixer block.

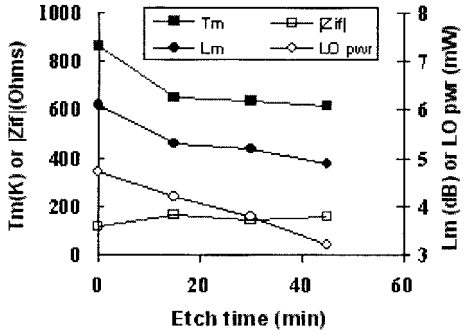


Fig. 6. Mixer performances as a function of etch time for diode A. RF frequency was 240 GHz.

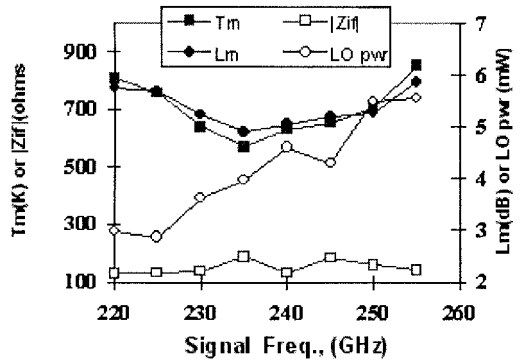


Fig. 7. Measured DSB mixer response of diode D at 1.5 GHz IF.

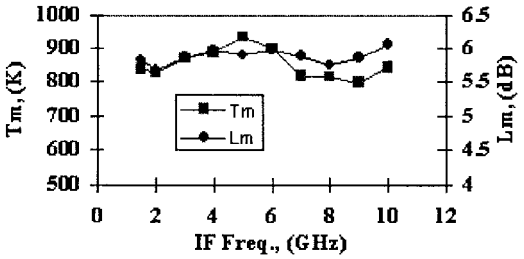


Fig. 8. IF frequency sweep of diode E. LO is 119.83 GHz with 3.6-mW power. IF output impedance ranges between 100–150 Ω.

with a finite-difference time-domain (FDTD) simulation, as described in [16], and the computed response is shown in Fig. 4.

B. Waveguide Mount

The waveguide-mixer mount design described in [7] demonstrated excellent performance for IF's up to 8 GHz, but the performance degraded significantly at 10 GHz due to a resonance in the relatively long transmission line between the LO guide and the K-connector bead at the IF output port. A modified block design is shown in Fig. 5. The IF resonance is removed by shortening the distance between the LO and signal waveguides by a factor of two. An added advantage to shortening this distance was an LO power reduction due to reduced waveguide path loss.

IV. Mixer Performance

The mixer noise performance was measured using a computer-controlled-mixer noise test system utilizing room temperature and liquid nitrogen loads, and is detailed in [17].

A. Effect of Parasitic Capacitance

In order to ascertain the quantitative effect of pad-to-pad capacitance on RF performance, diode A of Tables I and II was mounted in the mixer block, RF tested, placed intact in an oxygen plasma etch for 15 min, and then remeasured a total of three times. The device $I(V)$ was found to change only slightly, until the fourth etch cycle, when one of the anodes degraded significantly. Fig. 6 shows the mixer performance as a function of etch time. As can be seen, the parasitic-capacitance reduction results in better mixer performance and lower LO power requirement.

B. RF and IF Bandwidth

The mixer RF bandwidth was measured using a backward-wave oscillator (BWO) (110–130 GHz) as the LO source. Inherent LO noise cancellation allows even a "noisy" LO to be used as a pump [7]. RF bandwidth for diode D is shown in Fig. 7. The best noise temperature obtained was 570 K double sideband (DSB) with an IF frequency of 1.5 GHz. A nominal IF frequency scan for these diodes when placed in the waveguide mount of Fig. 5 is shown in Fig. 8. The IF resonance at higher frequencies is removed and the mixer performance is relatively flat across the desired IF band.

C. LO Power Requirement

Earlier mixers utilizing QUID devices have demonstrated mixing with 3–4 mW of LO power, but required 6–8 mW for optimum performance [7]. For the present devices, 3–4 mW of LO power is sufficient. This improvement in LO coupling can be attributed to improvements in block design and to lower parasitic QUID structures. Typical LO powers versus mixer performance characteristics are shown in Fig. 9. Optimum LO power is approximately 2.3 mW, but a noise temperature of 800 K DSB is possible with only 1.5 mW.

D. Single-Sideband-Mixer Performance

To measure the single-sideband performance of the mixer, a scanning Fabry–Perot interferometer (FPI) is inserted into the RF reference load path of the mixer. For 24-GHz sideband

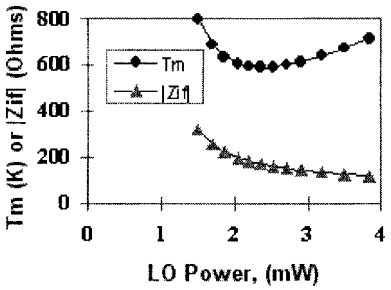


Fig. 9. Diode C DSB performances versus LO power. LO frequency is 119.83 GHz and IF is 1.5 GHz.

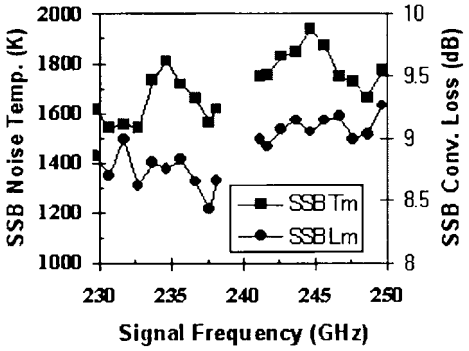


Fig. 10. Measured SSB performance of diode E. LO frequency is 119.83 GHz with 3.6 mW of LO power.

TABLE III
SUMMARY OF MIXER PERFORMANCE

Diode	T_m min K	RF Freq. GHz	LO pwr mW	Block
A	560	230	2.8	A2
	620	240	3.2	
B	670	240	2.2	B1
C	510	240	3.0	B1
D	570	235	4.0	A2
	630	240	4.6	
E	700	240	3.6	B1

ratio (SBR) measurements, the FPI is fitted with 100-line-per-inch nickel mesh grids. A range of grid spacings is chosen to allow at least two orders to pass through both sidebands of the mixer without aliasing. This is necessary to assess ratio measurement errors due to beam walk-off inside the FPI. The mixer conversion loss and noise temperature is then measured as a function of grid spacing. The measurement is repeated several times at each IF frequency to average out noise and drift, and the SBR is determined graphically from the plot of conversion loss versus grid spacing. The measured SBR is then used to plot the true single-sideband response of the mixer given in Fig. 10. The measurement shown was performed with diode E. The LO frequency and power was 119.83 GHz and 3.6 mW, respectively. The mixer was tuned for optimum performance at 9 GHz IF.

E. Summary of Mixer Performance

Table III lists the measured performance of the six mixer diodes in Tables I and II measured at 1.5-GHz IF. In certain cases, T_m improves slightly at 2-GHz IF frequency. For example, for diode E, T_m drops to 540, while the T_m of diode C drops down to 490 K. Block A2 has the longer LO microstrip channels and associated IF resonance at 10 GHz. Block B is the design shown in Fig. 5.

Our present results, although superior to other subharmonic mixers, are still a factor of 1.4 worse than the best-ever whisker-contacted fundamental mixer [18] at these frequencies. Even so, the practical advantages of SHPM mixers make them the option of choice for our space-borne application.

V. CONCLUSION

240-GHz waveguide-based subharmonic mixers with improved sensitivity and broad IF bandwidth have been demonstrated. The QUID technology has enabled the implementation of quartz-based fully integrated circuits in waveguide blocks for easy mounting and low loss. The performance of these mixers is consistent over a number of different device batches made by different processes at the UVa and JPL. The improved performance of the mixer is attributed to lower parasitic devices and an improved waveguide block. Sensitivities from these subharmonic mixers are slightly better than those obtained from discrete devices and are approaching the best sensitivities reported from whisker-contacted fundamental mixers at the same frequencies. Given the advantages of lower LO frequency requirements and greater IF bandwidth, a properly designed and implemented subharmonic mixer is a strong contender for space-borne applications at these frequencies. The availability of a high-frequency low-loss fully integrated diode/circuit structure will allow more complex multielement mixer/multiplier circuitry in the future.

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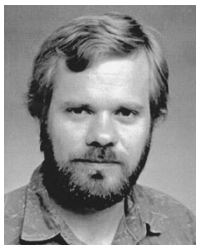
Dexter A. Humphrey, photograph and biography not available at the time of publication.

Trong-Huang Lee (S'89–M'98) was born in Taipei, Taiwan, R.O.C., in July 1964. He received the B.S. degree in electrical engineering from National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1986, and the M.S. and Ph.D. degrees from the University of Michigan at Ann Arbor, in 1990 and 1994, respectively.

Since 1994, he has been with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, where he is involved with the development of very high-frequency diodes and circuits. His current interests include high-frequency nonlinear devices and RF micromachined integrated circuits.

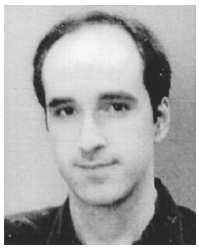


Robert J. Dengler was born in Whittier, CA, in July 1963. He received the B.S. degree in electrical and computer engineering from the California State Polytechnic University, Pomona, in 1989.

He is currently a Member of the engineering staff at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, where he is primarily involved with the development of test instrumentation for, and design, construction, and testing of submillimeter receivers and components for space-borne applications.

John E. Oswald received the B.S. and M.S. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1992.

Since 1992, he has been with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, where he is currently a Member of the engineering staff.



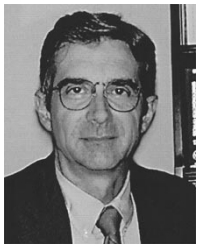
Andrew J. Pease was born in Glendale, CA, in 1971. He is currently working toward the B.S. degree in biology from California Polytechnic State University, Pomona.

In 1991, he joined the Sub-Millimeter Advanced Technology Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, where he is responsible for the micro-fabrication and assembly of submillimeter and terahertz mixers, multipliers, and related components.

Mr. Pease was the recipient of two NASA Nova Awards and a Jet Propulsion Laboratory Technical Achievement Award.

Suzanne C. Martin (S'89–A'90) received the B.S. and M.S. degrees in electrical engineering from Brown University, Providence, RI, in 1985 and 1991, respectively.

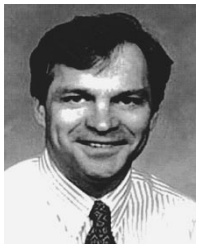
From 1985 to 1989, she was a Research Engineer at Brown University, where she designed and fabricated germanium photo diodes and MOSFET's. She is currently a Member of the technical staff at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, where she is involved in the fabrication of mixer and varactor diodes for submillimeter-wave applications and high electron-mobility transistor (HEMT) processing for communications applications.



William L. Bishop (S'88–A'88) received the B.S. degree in engineering science from the University of Virginia, Charlottesville, in 1969.

He is currently a Research Scientist in the Semiconductor Device Laboratory, University of Virginia. He is a founder and Vice President of Virginia Diodes, Inc., Charlottesville, VA. For the past 15 years, he has been actively involved in the design and fabrication of millimeter- and submillimeter-wavelength Schottky diodes. His primary interest is the development of new technology for the fabrication of whisker-contacted and planar diodes, which improves performance, reliability, and yield.

Mr. Bishop is a member of Sigma Xi.



Thomas W. Crowe (S'82–M'82–SM'91) received the B.S. degree in physics from Montclair State College, Montclair, NJ, in 1980, and the M.S.E.E. degree and Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, in 1982 and 1986, respectively.

He remained at the University of Virginia, where, in March 1986, he became a Research Assistant Professor of electrical engineering, a Research Associate Professor in July 1991, and a Research Professor in August 1997. Since January 1989, he has been the Director of the Semiconductor Device Laboratory, and, in 1996, he was elected Director of the Applied Electrophysics Laboratories. He is also a founder of Virginia Diodes, Inc., Charlottesville, VA. His main areas of interest include the development of high-frequency semiconductor devices and the optimization of such devices for use in low-noise submillimeter-wavelength receivers. His current research is focused on the investigation of novel device structures for high-frequency applications, development of solid-state power sources for terahertz frequencies, and the use of planar-device technologies to allow the routine implementation of heterodyne receivers on space platforms for radio astronomy and studies of the chemistry of the upper atmosphere.

Peter H. Siegel (S'77–M'83–SM'98) was born in New Rochelle, NY, in August 1954. He completed his undergraduate work at Colgate University, Hamilton, NY, in 1976, and received the M.S. and Ph.D. degrees in electrical engineering from Columbia University, New York, NY, in 1978 and 1983 respectively.

In 1975, he was with the NASA Goddard Space Flight Center, Institute for Space Studies, New York, NY, where he worked on millimeter-wave mixers and multipliers. In 1984, he moved to the Central Development Laboratory, National Radio Astronomy Observatory, where he spent three years working on the millimeter receivers for the NRAO Kitt Peak 12 meter telescope. In 1989, he joined the Advanced Devices Group, California Institute of Technology, Jet Propulsion Laboratory (JPL), Pasadena. In 1994, he formed and became Supervisor of the JPL Submillimeter Wave Advanced Technology (SWAT) team, which is currently composed of approximately 20 engineers and scientists who provide technology development and instrumentation support for NASA's advanced millimeter and submillimeter-wave missions. His research interests include millimeter- and submillimeter-wave devices, components, and subsystems.