A Planar Wideband Millimeter-Wave Subharmonic Receiver

B. K. Kormanyos, C.C. Ling and G.M. Rebeiz

NASA/Center for Space Terahertz Technology
Electrical Engineering and Computer Science Department
University of Michigan
Ann Arbor, MI 48109-2122

P.H. Ostdiek, W.L. Bishop and T.W. Crowe

Semiconductor Device Laboratory
Department of Electrical Engineering
University of Virginia
Charlottesville, VA 22903

ABSTRACT

A wideband planar subharmonic mixer has been designed for millimeter-wave operation. The receiver consists of a back-to-back Schottky-diode pair integrated at the base of a wideband log-periodic antenna. The antenna is backed by a hyperhemispherical lens and tested at 178.5GHz with a 90GHz local oscillator. The results indicate a single-sideband conversion-loss of -12.8dB without any RF or IF matching networks. The subharmonic monolithic approach results in an inexpensive wideband receiver and the design can be easily extended to receiver arrays.

INTRODUCTION

Millimeter-wave subharmonic mixers use an anti-parallel diode pair to generate a non-linear conductance waveform at twice the frequency of the applied LO signal [1,2,3]. Therefore, the required LO frequency is half that of the RF signal, and this offers unique advantages over fundamental single-ended mixers. Millimeter-wave subharmonic mixers require simpler filter-circuits designs and eliminate the use of potentially lossy quasi-optical diplexers. However, subharmonic mixing requires a well matched back-to-back diode pair for optimal performance. This is difficult to achieve at millimeter-wave frequencies with discrete devices, especially if the diodes are of the whisker-contacted type.

We have solved this problem and considerably simplified the receiver design by"integrating" a planar back-to-back GaAs Schottky-diodes at the apex of a wideband log-periodic antenna [4]. The log-periodic antenna catches both the RF and LO signals, and the LO signal is injected quasi-optically using a simple dichroic filter (Fig. 1). The anti-parallel diodes are fabricated at the University of Virginia, and exhibit very low parasitic capacitances [5]. An optional matching network can be integrated at the antenna apex for better RF power transfer into the diode pair. The design results in an inexpensive monolithic receiver with potentially the same conversion-loss as single-ended waveguide mixers.

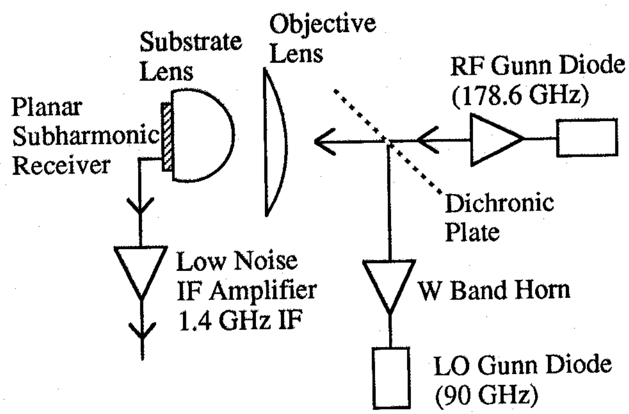

Figure 1: A quasi-optical subharmonic receiver with a dichroic plate for LO injection.

CH2870-4/91/0000-0213$01.00 © 1991 IEEE

ANTENNA DESIGN AND MEASUREMENTS

The antenna is a wideband self-complementary log-periodic antenna with $\sigma = 0.5$ and $\tau = \sqrt{2}$ designed to cover the 60GHz to 280GHz band. The values of σ, τ yield a wideband antenna that maps onto itself every octave. The log-periodic antenna is placed on the back of a hyper-hemispherical lens to eliminate substrate modes and to yield a unidirectional pattern [6]. A polystyrene quarter-wave matching layer is used at the silicon-air interface to eliminate any reflected power from the lens [7]. The antenna input impedance is independent of frequency, and is related to the mean dielectric constant by:

$$Z_{ant} = \frac{189\Omega}{\sqrt{0.5(1+\epsilon_r)}} \qquad (1)$$

where 189Ω is the impedance of any self-complementary structure in free-space, and ϵ_r is the relative dielectric constant of Silicon (or GaAs). This yields an impedance of 75Ω for a log-periodic antenna on a Silicon lens.

The Schottky diodes were forward biased and operated in the video detection mode for pattern measurements at 90 and 180GHz. The results show excellent E and H-plane patterns with a co-polarized directivity of 24.6dB at 180GHz (Fig. 2). The high cross-polarization component should not affect the coupling efficiency for radiometric applications but will reduce the quasi-optical local oscillator coupling by 1.5dB. The 180GHz pattern is free from sidelobes and will match well an f/2 reflector system.

DIODE DESIGN AND MEASUREMENTS

The anti-parallel diode chip, shown in Figure 3, was developed and fabricated at the University of Virginia for use in a 183GHz waveguide receiver [5]. The chip is 250μm long, 125μm wide and approximately 50μm thick and was soldered on the antenna using a low-temperature process. A surface channel technology has been used to eliminate the conducing path between the anode and cathode pads [8]. The parasitic capacitance

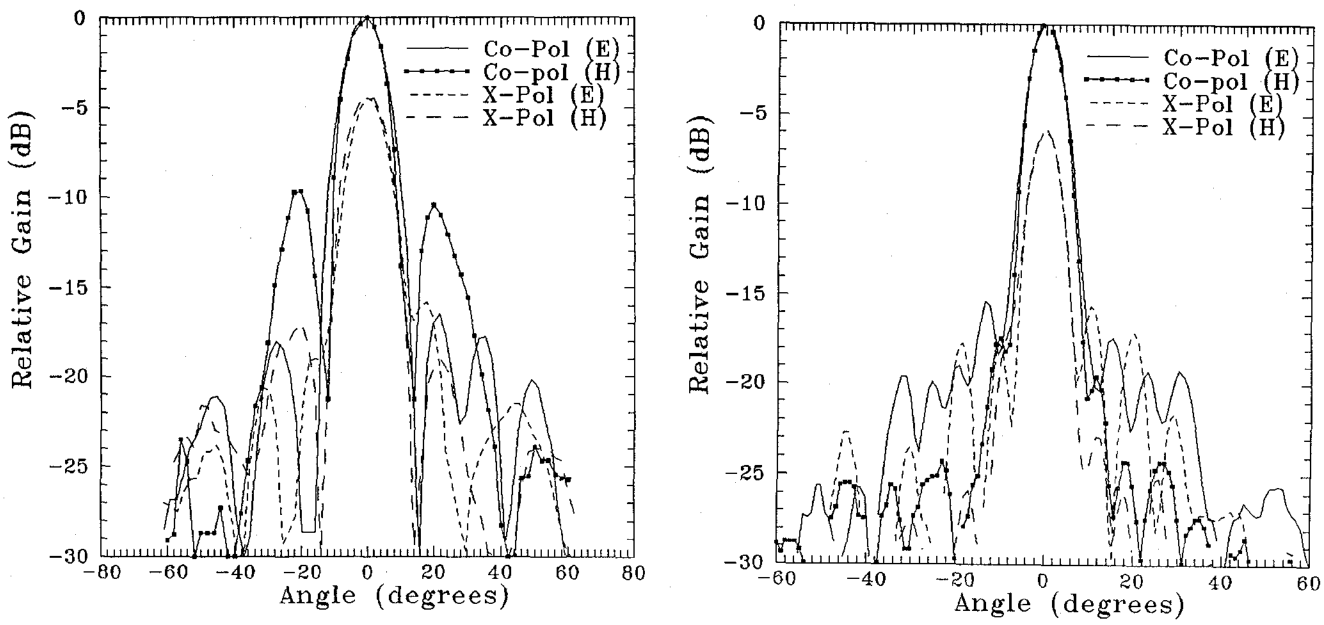

Figure 2: Measured antenna patterns at 90GHz (left) and 180GHz (right). The high cross-polarization component should not affect the coupling efficiency for radiometric applications but will reduce the quasi-optical local oscillator coupling by 1.5dB.

can be further minimized by removing the semi-insulting GaAs substrate and replacing it with quartz. Furthermore, the quartz substrate can be easily removed after the chip is soldered in place by simply dissolving its adhesive [9]. The diode used in this research has a measured series resistance of 11Ω and a zero-bias capacitance of roughly 4fF. The total parasitic capacitance for the quartz-diode is estimated at 3fF, thereby yielding a figure-of-merit cutoff frequency of approximately 2THz. The measured I-V curve for the diode pair after being mounted at the antenna terminals is shown in Fig. 4. The anodes are virtually identical with an ideality factor n = 1.2 and a turn on voltage of 0.7V at 1μA.

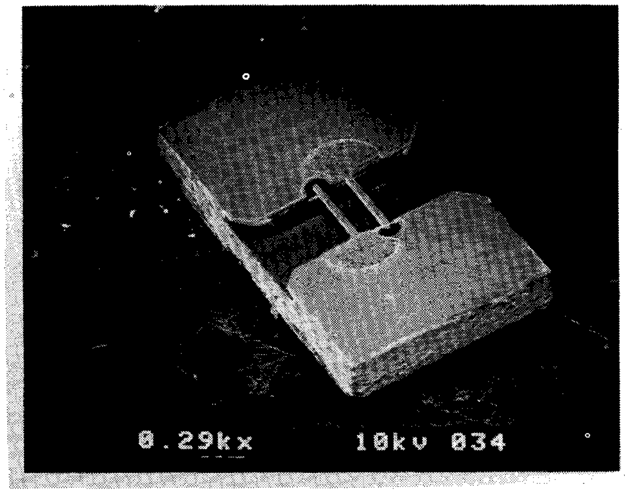

Figure 3: SEM picture of the surface-channel diode. The underlying substrate is then etched and the diode is mounted on the antenna.

MIXER MODELING AND MEASUREMENTS

A non-linear mixing program was written at the University of Michigan for the analysis of subharmonic mixers [10]. The program takes into account the asymmetrical I-V curve of the back-to-back diodes. The higher-order terminating impedances are assumed to be resistive and equal to 75Ω in parallel with the parasitic capacitance of the diode. The analysis indicate that a conversion loss of 9.9dB is attainable at 180GHz without an RF matching network. The corresponding RF and IF impedances are $26 - j30\Omega$ and 60Ω, respectively. It is possible to increase the conversion loss by 2dB with an RF matching network at the expense of a narrowband design.

The single-sideband mixer performance was measured at 178.5GHz using a local oscillator at 90 GHz. The antenna directivity and substrate-lens dielectric losses (estimated at 0.5dB) have been normalized out of the measurements. The directivity is measured by a full two- dimensional co- and cross-polarized scans of the antenna pattern. The conversion loss presented below (Fig. 5) is defined as the power measured at the IF port divided by the 178.5GHz RF power available at the antenna terminals. It includes the RF and IF mismatch losses and the intrinsic conversion loss of the subharmonic mixer. A minimum conversion loss of 12.8dB$\pm$0.5dB was measured with an esti-

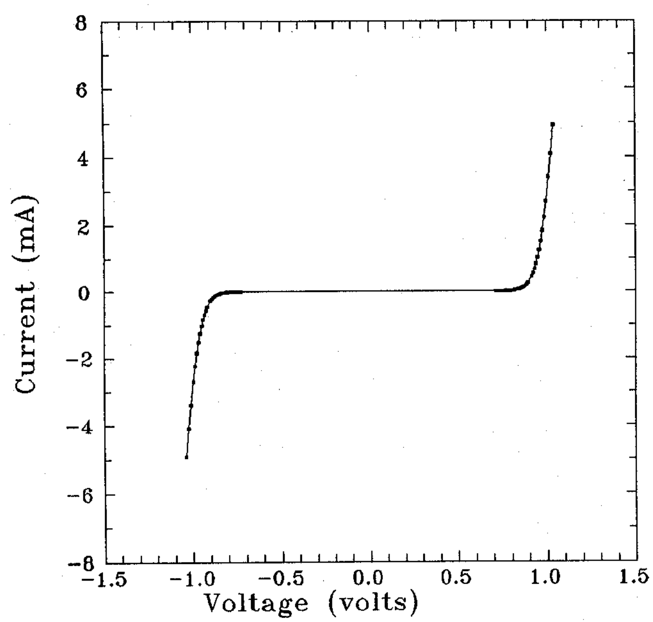

Figure 4: The measured dc I-V curve of the back-to-back Schottky diodes. The diode parameters are determined by least-square fitting of the equation $I = I_s \exp(V/nV_T - IR_s)$. The fitted parameters are $I_s = 7x10^{-17}$, n = 1.2 and $R_s = 11\Omega$.

mated local oscillator power of 4.5mW available at the antenna terminals. It is possible to further reduce the conversion loss by 1- 2dB with more LO power and we are currently optimizing the local oscillator injection into the mixer. The receiver isotropic conversion gain, defined as the measured IF power divided by the 178.5GHz RF power received by an isotropic antenna, is (24.6 – 0.5 – 12.8dB) = 11.3dB. The isotropic conversion gain is increased by 3dB for double-sideband applications and by another 1dB for radiometric applications where polarization purity is of no importance.

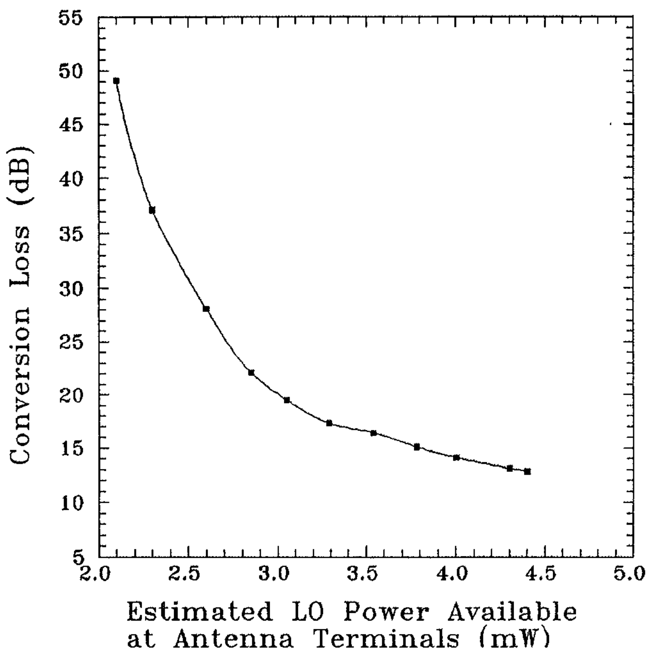

Figure 5: Measured subharmonic conversion loss at 178.5GHz with the antenna gain normalized out. The measured conversion loss is 12.8dB ± 0.5dB and can be further reduced with a higher LO power.

ACKNOWLEDGEMENTS

This work was supported by the NASA/Center for Space Terahertz Technology at the University of Michigan, and at the University of Virginia by NSF grant ECS-8913169, US-Army and Aerojet Electrosystems.

REFERENCES

[1] T.F. McMaster, M.V. Schneider, and W.Snell, Jr.,"Millimeter-wave receiver with subharmonic pump," *IEEE Trans. Microwave Theory Techn.*, vol. MTT-24, pp. 948-952, December 1976.

[2] E.R. Carlson, M.V. Schneider and T.F. McMaster, "Subharmonically pumped millimeter-wave mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 706-715, October 1978.

[3] I.Galin, "An improved structure for subharmonically pumped millimeter-wave mixers," *12'th Int. Conf. Inf. Millimeter Waves*, Dec. 1987.

[4] R.H. Duhamel and D.E. Isbell, "Broadband logarithmically periodic antenna structure," *IRE National Convention Record*, Part I, pp. 119-128, 1957.

[5] P.H. Ostdiek, T.W. Crowe and I. Galin, "Integration of an anti-parallel pair of Schottky barrier diodes in millimeter-wave mixers," *15'th Int. Conf. Infrared Millimeter Waves*, Orlando, Florida, December 1990.

[6] D.B. Rutledge, D.P. Neikirk and D.P. Kasilingam, "Integrated-Circuit Antennas," *Infrared Millimeter Waves*, vol. 10, Chap. 1, K.J. Button, ed., Academic Press, New York, 1983.

[7] C.E. Zah and D.B. Rutledge, "A polystyrene cap for matching a silicon lens at millimeter-wavelengths", *J. Infrared Millimeter Waves*, vol.6, pp. 909-918, September 1985.

[8] W. L. Bishop et. al., " A novel whiskerless diode for millimeter-wave and submillimeter-wave applications," *IEEE MTT-S Intl. Symp.*, pp. 607-610, Las Vegas, Nevada, June 1987.

[9] W. L. Bishop et. al., "A micron-thickness planar Schottky-diode chip for terahertz applications with theoretical minimum parasitic capacitance," *IEEE MTT-S Intl. Symp.*, pp. 1305-1308, Dallas, Texas, May 1990.

[10] A.R. Kerr, " Noise and loss in balanced and subharmonically pumped mixers: Part I-Theory," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, No. 12, pp. 938-943, December 1978.