A Comparison of Planar Doped Barrier Diode Performance Versus Schottky Diode Performance in a Single Balanced, MIC Mixer with Low LO Drive

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***Abstract*—This paper demonstrates that an unbiased GaAs planar doped barrier (PDB) diode, single balanced, *Ku*-band mixer achieves conversion loss performance comparable to a bias-optimized GaAs Schottky design at low local oscillator (LO) power levels for identical RF circuits. An experimental, side-by-side, performance comparison as a function of LO power is presented along with a harmonic balance (HB) simulation. The PDB diode is of interest for its zero-bias requirement and the high pulsed peak power handling potential for low-cost radars.**

I. Introduction

THE PLANAR doped barrier (PDB) diode was reported by Malik *et al.* [1], [2] as a new and novel majority carrier, rectifying barrier device. The semiconductor structure lends itself to the independent and continuous control of the barrier height and asymmetry of the *I–V* characteristics.

The principal motiviation for this work was Dale's [3] initial test results with a *single-ended mixer* which show a marked reduction in LO power levels for the *unbiased* GaAs PDB design compared to that of the GaAs Schottky. This result and the elimination of dc bias lines generally required for the Schottky design, provides a cost advantage for multichannel radar and communication systems since LO power generation is expensive. Dale's tests also demonstrated that low-frequency noise generation (IF $<$ 1 MHz) was significantly less for the PDB than for either a silicon or GaAs Schottky diode in the single-ended mixer application. Pulsed burnout data [3], [4] showed burnout levels for a PDB in the 200–400-W range compared to the 0.5–1-W range for the medium-barrier silicon Schottky. The significant improvement in the PDB's ability to handle high pulsed power without burnout promises to eliminate the need for a limiter diode stage prior to the mixer for low-cost, pulsed radars.

This effort addresses a lack of design information and comparative performance data for *balanced mixers* comparing an *unbiased* GaAs PDB and a *bias optimized* GaAs Schottky. This investigation focuses on the design and performance comparison of two, *Ku*-band, balanced mixers with identical RF circuits. Conversion loss of less than 8 dB for a LO power of 5 dBm was the design goal. A performance comparison as a function of LO power for identical balanced designs was generated to identify the breakpoints in performance and thereby provide insight into the applicability of each diode type.

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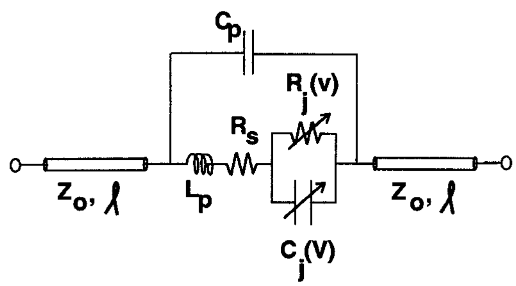

Fig. 1. Device electrical equivalent circuit.

II. Device Characterization

In order to perform a harmonic balance analysis of the mixer, discussed in Section IV, it was necessary to generate analytical circuit models for both the Schottky and the planar doped barrier (PDB) diodes consistent with experimental performance. The standard RF equivalent circuit for the *beam lead package* is illustrated in Fig. 1. Briefly, L_p accounts for stray series package inductance, C_p models the package capacitance, and R_s accounts for the finite resistivity of the device's active region. At millimeter-wave (MMW) frequencies inclusion of the electrical length of the diode was found to be critical in obtaining an accurate device model. Therefore, the gold ribbon on each side of the beam lead is modeled by microstrip transmission line formed by the ribbon and the alumina substrate material to which the beam lead diode is attached in the MMW mixer circuit. For the beam lead packages examined in this investigation, C_p was found to be negligible. The analytical expression for $C_j(V)$ for the Schottky diode is available in the literature [5] and $C_{\rm PDB}(V)$ is, to first order, a constant given by

$$C_{\rm PDB} = \frac{\epsilon_s A}{L_1 + L_2} = C_{j0} = \text{constant} \quad (1)$$

where L_1 and L_2 are the lengths of the intrinsic regions of the PDB diode [6]. $R_j(V)$ is neglected for each device when the device is well into forward bias and assumed infinite when the device is reverse-biased. These assumptions were consistent with our observations.

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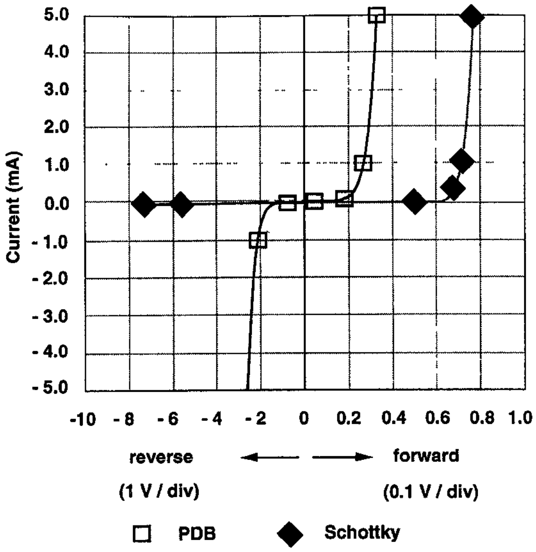


Fig. 2. I–V characteristics of Schottky DMK2791 and PDB DC1822 diode plotted on a linear scale.

TABLE I
DIODE CHARACTERIZATION DATA SUMMARY

Characteristic	Schottky DMK2791	PDB DC1822
CV Equation (pF)	$\frac{.03}{\sqrt{1-\frac{V_{applied}}{.75}}}$	.12
Series Resistance R_s	12 Ω	8 Ω
Junction Capacitance C_{jo}	.03 pF	.12 pF
Package Inductance L_p	.03 nH	.02 nH
Package Capacitance C_p	0 pF	0 pF
* Microstrip line width w	.006 in.	.006 in.
* Microstrip line length l	.008 in.	.006 in.
Cutoff frequency f_c	442 GHz	166 GHz

* Note: Microstrip line substrate parameters:
Substrate thickness h = .015 in.
Dielectric constant ε_r = 9.9

The general I–V equation for a PDB diode is

$$I_{\rm PDB} = I_{0\,\rm PDB}\left[\exp\left(\frac{q\alpha_2 V}{kT}\right) - \exp\left(-\frac{q\alpha_1 V}{kT}\right)\right] \tag{2}$$

where α_1 and α_2 are the forward and reverse *geometric factors.* With only a forward bias, it approximates the Schottky expression as

$$I_{\rm PDB} \cong I_{0\,\rm PDB}\left[\exp\left(\frac{q\alpha_2 V}{kT}\right)\right]. \tag{3}$$

DC measurements determine the analytic expressions for the device's I–V characteristic by finding the saturation current, R_s, as well as the *ideality factor* and the *geometric factor* for both the Schottky and PDB devices, respectively. Details of the procedures are standard and available in [6]. Microwave/millimeter-wave (MW/MMW) measurements determine the rest of the circuit elements.

The MMW GaAs Schottky barrier beam lead diode used in the balanced mixer circuit is manufactured by Alpha Industries; part number DMK2791. The MMW GaAs PDB beam lead device is produced by GEC Plessey Semiconductor; part number DC1822. I–V curves measured and plotted on a linear scale for both devices, are shown for comparison in Fig. 2. If we define the turn-on voltage as that voltage where the forward current exceeds 1 mA, then the turn-on voltage for the PDB device occurs at a significantly lower voltage than that of the Schottky. This is due to the fact that the lower barrier potential formed in the PDB device results in a larger saturation current for the PDB diode than for the Schottky diode. Fig. 2 also shows that for negative applied voltage the PDB device conducts a significant amount of reverse current, as expected.

The PDB device is fabricated for a very low turn-on voltage in the forward current direction and a relatively large turn-on voltage in the reverse current direction; an *asymmetric* I–V characteristic (note the change of scale on the left side of the ordinate). Device physics [6] show that the degree of asymmetry in the PDB I–V characteristic is governed by the relative positioning of the p^+ layer within the intrinsic region.

Logarithmic plots were made from the measured I–V data for both diodes and the dc characteristic parameters were determined and summarized in Table I. The I–V equations for the Schottky and PDB diodes at room temperature are

$$I_{\rm Sch} = 7.14 \times 10^{-14}\left[\exp\left(\frac{V}{(0.025)(1.21)}\right) - 1\right] \tag{4}$$

and

$$I_{\rm PDB} = 3.8 \times 10^{-7}\left[\exp\left(\frac{(0.80)V}{0.025}\right)\right]. \tag{5}$$

The PDB expression is valid as long as the applied voltage is greater than that necessary to turn on the device in the reverse direction. These equations were used in the harmonic balance mixer circuit analysis.

A. MW/MMW Characterization

The beam lead devices were mounted and measured in a MMW microstrip test fixture. The device and microstrip lines were mounted inside a narrow channel formed by two sidewalls of the test fixture and enclosed by a metal cover. The cutoff frequency of the partially dielectric-filled rectangular waveguide formed by the channel and cover was calculated and the dimensions are chosen such that the possibility of exciting a waveguide mode in the fixture within the frequency band of interest was eliminated, i.e., the quasi-TEM microstrip mode was the only mode allowed to propagate. This criterion is particularly important when evaluating devices at millimeter-wave frequencies. The channel cross section used throughout the design was 0.135 in × 0.200 in. ($H \times W$). The microstrip substrate material is 0.015-in-thick alumina with a relative dielectric constant of 9.9.

One side of the beam lead attaches to a short length of 50 Ω microstrip transmission line and the other side is attached to the grounded brass fixture. The one-port S_{11} measurements

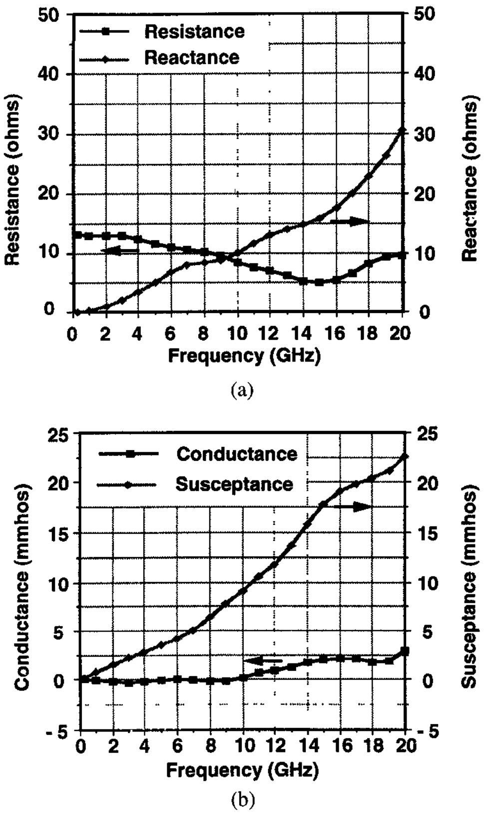


Fig. 3. DC1822 PDB de-embedded data. (a) 10-mA forward-biased case determines the parasitic inductance L_p and series resistance R_s. (b) The 0-V reverse bias determines the PDB junction capacitance.

were performed with an automatic vector network analyzer (VNA) with coaxial connectors on its measurement ports. A coaxial-to-microstrip (K-connector) adapter mated the VNA to the beam lead test fixture.

The measured RF data include the electrical properties of the coaxial-to-microstrip transition, a short length of 50 Ω microstrip line and the beam lead diode. In order to characterize the beam lead diode only, these effects must be removed from the measured data. A novel de-embedding procedure was developed during the course of this work [6]. Other de-embedding techniques [7], [8] are also available. Herman's extended thru-reflect-line (ETRL) [9] is an excellent choice.

Once the S-parameter model for the two-port, representing the transition and microstrip line length, was obtained, the effects of this network on the data measured at the VNA calibration plane were de-embedded with a standard linear circuit simulation software package; Touchstone or Libra. This procedure set the effective measurement reference plane at the diode terminals.

RF impedance measurements were performed on both diodes at a forward current level of 10 mA. This allowed the determination of the inductance L_p and the series RF resistance R_s. The data were measured from 40 MHz–20 GHz. The zero-bias susceptance measurements determined the C_{j0} value for the PDB. Plots of the PDB results are given in Fig. 3. Additionally, the same measurements were made for various reverse-bias voltages for the Schottky diode establishing the $C(V)$ relationship.

Table I, as well as (4) and (5), summarize all the diode data needed to perform a harmonic balance analysis. The C_{j0} of the DMK2791 Schottky is one fourth that of the DC1822 PDB, consequently, the Schottky can be used into the Ka-band frequency range, whereas, the PDB is near the limit of it's frequency range at Ku-band.

III. Balanced Mixer Design

A. Ku-Band Mixer Description

The design goals for the balanced mixer were

$$\begin{aligned} f_{\mathrm{RF}} &= 16.0\ \mathrm{GHz}, \quad P_{\mathrm{RF}} = -10.0\ \mathrm{dBm} \\ f_{\mathrm{LO}} &= 15.5\ \mathrm{GHz}, \quad P_{\mathrm{LO}} < +5.0\ \mathrm{dBm} \\ f_{\mathrm{IF}} &= 0.5\ \mathrm{GHz} \\ L_c &< 8.0\ \mathrm{dB} \end{aligned} \tag{6}$$

where L_c is mixer conversison loss.

The Ku-band balanced mixer design was based on the circular ring configuration described by Maas [10]. A schematic of the two circuits is shown in Fig. 4. The mixer consists of a 180° octagonal ring hybrid coupler, a low-pass filter, and two high-frequency coupled line capacitors. In addition, a quarter-wavelength line bias section, absent from the PDB design shown in Fig. 4(a), is included in the Schottky mixer design of Fig. 4(b). The figure illustrates that the nonlinear devices, oriented as shown, are attached to two ports of the hybrid and the RF and LO signals are input at the other two hybrid ports. Electrical properties of hybrid couplers mutually isolate the RF and LO ports from one another, as well as, the two diode ports. The coupled line capacitors, at the RF and LO ports, provide low insertion loss at the RF and LO frequencies, while rejecting the IF signal generated in the octagonal hybrid and providing a dc block. The low-pass filter (LPF) passes the IF signal while presenting a high impedance, ideally an open circuit, to the hybrid at the RF and LO frequencies. A 100-pF series chip capacitor at the LPF output provides a dc block.

The Schottky mixer requires bias in order to achieve low conversion loss at low LO power levels. The bias acts as a variable tuning mechanism as well as setting the operation at the knee of the I–V curve. Fig. 4(b) shows that the bias network consists of two 27-pF chip capacitors, a $\lambda_g/4$ high-impedance line and a current-limiting resistor. The cathode of the upper Schottky diode attaches to the octagonal ring hybrid while the anode attaches to the top metallization of one of the 27-pF chip capacitors, thus providing a low-impedance path to ground at the LO frequency. Since the low impedance offered by the other 27-pF chip capacitor in the bias network is translated through a high-impedance quarter-wavelength line, an open circuit is seen at the anode of the upper Schottky diode looking back towards the dc bias supply. The dc blocks route the bias current through the Schottky diodes to ground.

For the lower Schottky diode, the cathode is attached directly to the grounded fixture and the anode is attached to the ring. The two diodes are attached to the ring with opposite polarities. This arrangement is due to the 180° phase difference the LO signal experiences when traveling between the LO port

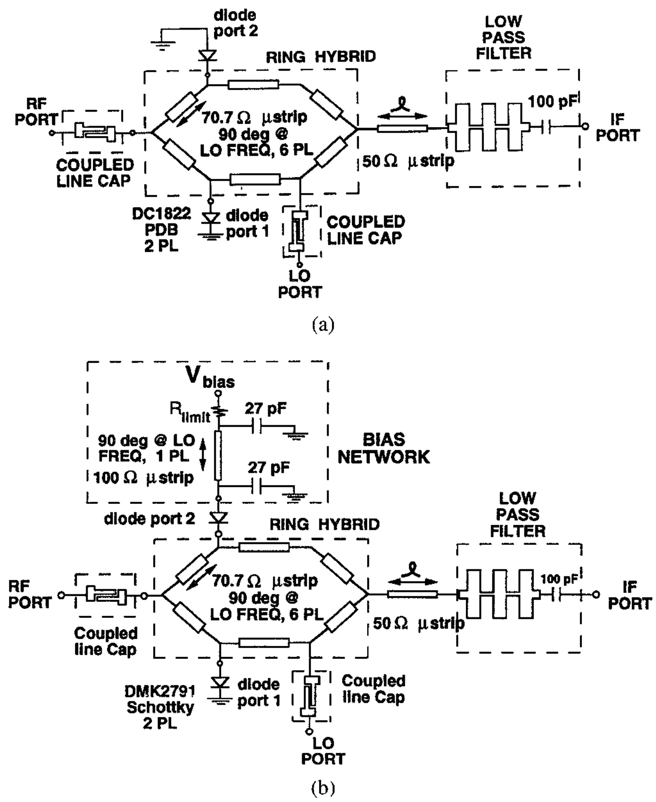


Fig. 4. (a) PDB mixer schematic and (b) Schottky diode mixer schematic.

to diode port 2, relative to the phase shift from the LO port to diode port 1. Using this arrangement, the IF currents generated in the mixer by each nonlinear device add constructively at the IF port [10].

The PDB diode balanced mixer shown in Fig. 4(a) is identical to the Schottky mixer design except no bias network is required. Both PDB diodes are attached from the octagonal ring directly to ground. The elimination of the bias network significantly reduces the cost of the PDB design. Except for diode bonding, the mixer is now a printed circuit.

B. Design Procedure

The five-port octagonal ring dimensions were optimized over a 2-GHz bandwidth to present the appropriate 3-dB power split and the 0 and 180° phase differential between the diode ports for the RF and LO ports, respectively. The worst case computed RF port return loss was -12.25 dB at the design frequency. The isolation between the RF and LO port was calculated to be greater than 40 dB at both the RF and LO frequencies. The worst case isolation between the diode ports was 17.5 dB. The low-pass filter (LPF) is a five-section Chebychev filter, designed within the waveguide channel, for an insertion loss of 0.20 dB, return loss of better than 20 dB at the IF, and signal rejection of greater than 30 dB at 15.5 GHz. The LPF is attached to the ring at a convenient location with a 50-Ω microstrip line a distance l from the ring. This distance is critical to achieving good mixer performance; $l = 0.075$ in. for this design. The microstrip coupled line capacitor used a coupled line length of $\lambda_g/4$ at the LO frequency; line spacing was set to 0.001 in. Simulated insertion loss and return loss at 15.5 GHz was 0.15 and -25 dB, respectively. Final mixer dimensional details are available in [6].

IV. Analysis and Measurement

Once the optimization in band was concluded, the passive circuit structure was analyzed over a band of frequencies spanning five harmonics of the LO frequency. The harmonic balance mixer analysis requires five harmonic frequencies of the fundamental tone (15.5 GHz) to predict mixer performance. Accurate simulation was necessary through 80 GHz. Conventional microwave circuit simulators are not sufficiently accurate in the millimeter-wave bands. Therefore, the electromagnetic (EM) circuit simulator, *Sonnet*, employing a moment method solution of Maxwell's equations, was used to analyze the individual elements of the mixer. The mixer circuit was subsectioned into smaller pieces with enclosing structure and each piece analyzed individually. The beam lead diode's microstrip line lengths were included in the Sonnet analysis. The S-parameter output, for each section, was then imported into a nonlinear circuit analysis program; EEsof's Libra. The Libra program provides a *harmonic balance* (HB) simulation technique, like that described by Maas [10] to analyze nonlinear circuits.

The elements in the diode equivalent circuit model, shown in Fig. 1, were accounted for in the HB simulation. Variables in the Libra large-signal diode model are junction capacitance, series resistance, saturation current, and ideality factor. The *Ku*-band PDB mixer simulation had one shortcoming. The Libra model was developed explicitly for the Schottky barrier diode. The implementation of $C(V)$ and $I(V)$ characteristics is accomplished with the $C(V)$ equation in Table I and (4), respectively. For the PDB diode, however, the desired equations are (1) and (2). For PDB diodes with small junction capacitance values, it was assumed that there was no significant error in using the Schottky form of the $C(V)$ equation with the appropriate value to model the ideally constant $C_{\mathrm{PDB}}(V)$ characteristic. Furthermore, when in the forward bias region, the $I_{\mathrm{PDB}}(V)$ (5) may be approximated by the Schottky $I(V)$ form, see (4), with the appropriate saturation current value and where the ideality factor n is set equal to the reciprocal of the PDB's measured geometric factor $1/\alpha$.

In order to validate the HB analyses, two *Ku*-band mixers, with identical layouts, one using biased Schottky diodes and the other using unbiased PDB diodes, were assembled according to Fig. 4. A computer-controlled mixer test system was assembled, calibrated over the frequencies of interest, and programmed to test both mixers. For the PDB circuit, the measured RF to LO isolation at 15.5 GHz was 23 dB. The return loss at the RF and LO ports for the appropriate frequencies and input power levels of -10 and $+5$ dBm was -12 and -10 dB, respectively.

The RF and LO operating condition

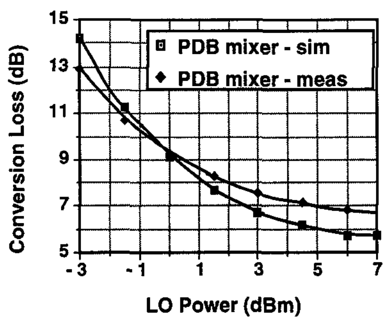
$$f_{\mathrm{RF}} = 16.0 \text{ GHz} \quad P_{\mathrm{RF}} = -10 \text{ dBm}$$
$$f_{\mathrm{LO}} = 15.5 \text{ GHz} \quad P_{\mathrm{LO}} = +3 \text{ dBm}$$

is used to initially compare the unbiased PDB and biased Schottky mixers. It is noteworthy that the Schottky was biased

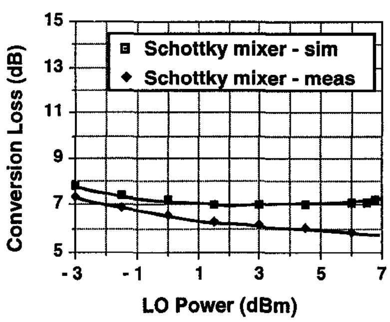
TABLE II
A COMPARISON OF MEASURED AND MODELED CONVERSION LOSS FOR BOTH MIXER CONFIGURATIONS AT AN L.O. POWER LEVEL OF ONLY +3 dBm

Mixer Type	$L_{c\ meas}$	$L_{c\ simul}$
PDB	7.5 dB	6.7 dB
Schottky *	6.2 dB	7.0 dB

* V_{bias} = 1.3 volts , R_{bias} = 50 Ω



(a)



(b)

Fig. 5. Measured versus modeled conversion loss data as a function of LO power for the *Ku*-band (a) PDB and (b) Schottky diode mixers.

at −1.3 V with a 50-Ω bias resistor. Also, the bias current through the Schottky diodes was LO-drive-dependent. With no LO drive, the bias current was at the microampere level. With LO drive levels of +3 dBm, the total bias current was 1.5 mA. Table II illustrates that the difference between predicted and measured conversion loss is only 0.8 dB and performance bested the 8-dB conversion loss design goal with 2-dB less LO power.

Conversion loss was also measured over a range of LO power levels while the RF power level was maintained at −10 dBm. Fig. 5 depicts modeled versus measured conversion loss, L_c, data for the PDB and Schottky mixers measured over a −3 to +7-dBm range of LO power. This comparison of the modeled and measured results shows excellent correlation for both diode types. In all cases, the difference between the measured and simulated conversion loss is one (1) dB or less for this range of LO power variation.

This level of correlation was possible as a result of the accurate circuit modeling of the mixer's passive geometry and the accurate device models developed during the course of this work. The difference between the measured conversion loss of the *unbiased* PDB and *bias optimized* GaAs Schottky mixer at the same LO power (+3 dBm) is only 1.3 dB. A conversion loss of 8 dB was achieved for a LO drive of only +2 dBm with an *unbiased* PDB diode besting the +5-dBm design goal. As the LO drive falls below +2 dBm, the PDB's conversion loss increases, unlike the biased Schottky counterpart. It should be noted, however, that the bias to the Schottky not only sets the operating sensitivity of the diode but also acts to RF tune the Schottky into the mixer circuit. The PDB mixer used no bias tuning or RF matching to optimize the mixer design. This was consistent with the initial criteria for direct comparison that both RF layouts be identical. If RF matching networks were installed prior to the diode, then lower LO power levels might be possible to achieve similar conversion loss. Due to the agreement between analysis and measurement, alternative PDB topologies may be evaluated via computer simulation using the circuit details given in [6].

V. CONCLUSION

The *unbiased PDB diode* provides comparable performance to the bias optimized GaAs Schottky diode in a balanced mixer geometry in applications requiring low LO drive power. With LO power levels as low as +2 dBm, the PDB mixer provided a conversion loss of 8 dB. A GaAs PDB diode mixer is a viable alternative for multichannel communication or radar systems where low LO power and zero bias tuning are primary design drivers. The authors believe that the real benefits of the PDB diode will be realized in the millimeter-wave frequency bands; when such devices become commercially available. A balanced mixer of this type could be fabricated in a MMIC format and directly connected to the output of a low-noise amplifier (LNA) for an integrated receiver application. In low-cost pulsed radars where a LNA is not required, the higher pulsed power-handling capability may eliminate the need for limiter circuits.

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