# SINGLE- AND DUAL-POLARIZED SLOT-RING SUBHARMONIC RECEIVERS

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**Abstract— Single- and dual-polarized subharmonic receivers have been developed for operation at W-band frequencies. The receivers are based on dielectric lens-supported, coplanar waveguide-fed slot-ring antennas integrated with uniplanar subharmonic mixers. The slot-ring antenna is capable of supporting two orthogonal modes offering the possibility of dual/multiple receive polarizations. The measured two-port isolation of the dual-polarized slot-ring antenna is better than -25 dB from 86-92 GHz. The measured DSB receiver noise temperature is 4300 K at an LO frequency of 45.0 GHz and an IF of 1.4 GHz. The corresponding DSB conversion loss is 12.2 dB. This includes lens reflection and absorption losses, backside radiation, RF feedline loss, and RF mismatch. When these losses are deembedded the results are in good agreement with the measured performance of the uniplanar subharmonic mixer alone. A matching cap layer on the lens and improved RF matching are expected to result in a DSB noise temperature of 1700-1900 K and conversion loss of 8-9 dB. Potential applications are compact, low-cost millimeter-wave receivers with fixed or variable polarization capabilities.**

## I. Introduction

There is considerable interest in the development of low-cost millimeter-wave receivers, transmitters, and imaging arrays for applications such as smart munition seekers, aircraft landing systems, and automotive collision avoidance sensors. An integrated circuit (IC) approach, consisting of planar antennas directly integrated with amplifiers and mixers, offers several advantages over waveguide-based systems.

A potential problem which arises in millimeter-wave ICs is that of substrate modes. In order to avoid power loss into these modes, very thin substrates ($\sim 0.05\lambda_d$) are typically required. A convenient method for eliminating substrate modes is to place an ungrounded CPW-fed slot-type antenna on a dielectric lens of roughly the same dielectric constant as the (thick) antenna wafer [1]. The lens appears as a dielectric half-space, and hence does not support surface waves. Furthermore, the antenna radiates preferentially into the dielectric, resulting in high-gain patterns without the need for a larger array of antenna elements and a corresponding increase in cost. The dielectric lens system has been extensively analyzed by Filipovic, *et al.* [2], and used successfully in quasi-optical double-slot Schottky-diode receivers at 90 [3] and 250 [4] GHz.

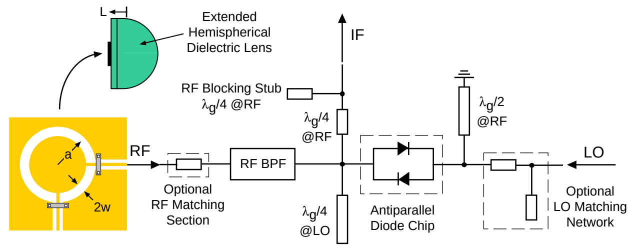


Fig. 1. Schematic of a single-(dual-)polarized slot-ring subharmonic recevier. a is the radius of the slot-ring, 2w is the width of the slot-ring, and L is the extension length of the extended hemispherical dielectric lens.

An alternative to the double-slot antenna geometry is the slot-ring antenna, which is attractive due to its compact geometry and potential for polarization diversity. Slot-ring antennas have been employed in millimeter-wave balanced mixer receivers [5] in which the LO and RF are injected quasi-optically and polarization duplexed by the antenna. By instead feeding the antenna at its two orthogonal ports with CPW lines, and utilizing planar mixers pumped by an on-chip LO distribution, the polarimetric capabilities of the antenna can be realized. Appropriate amplitude and phase adjustments between the two ports allows the synthesis of any polarization state [6]. In this work CPW-fed slot-ring antennas [7] are integrated with uniplanar subharmonic mixers [8] to realize single- and dual-polarized receivers at W-band frequencies. Subharmonic mixing is utilized due to the relative ease of LO distribution, and the inherent RF/LO isolation which is important in order to minimize the leakage of LO power to the antenna.

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## II. Receiver Design

A schematic of the receiver design is shown in Figure 1. The design frequency is 94 GHz with an IF bandwidth of 2-4 GHz. A single- or dual-polarized slot-ring antenna is placed at the center of the dielectric lens at a distance, L, from the hemispherical position called the extension length. A slot-ring-fed 24-mm diameter extended hemispherical silicon lens at 94 GHz has a maximum directivity of 27 dB around L=4400 $\mu$m (the synthesized elliptical position) [7]. The calculated reflection loss with this configuration is -2.7 dB, which contributes directly to the receiver noise figure, and may also affect the antenna impedance and radiation patterns. The incorporation of a matching cap layer should result in approximately 1.5 dB improvement in the reflection loss [2]. A lens with an optimal quarter-wave matching layer was not available at the time of this writing.

Single- and dual-polarized slot-ring antenna designs were simulated using HP Momentum [9] and the input impedance of the fabricated antennas was measured using on-wafer probing techniques. The die was placed on a 12.5 mm block of Stycast HiK[1] ($\epsilon_r$ =12) which was in turn placed on the probe station chuck. The residual reflection from the chuck was eliminated using time-domain gating. A TRL calibration was performed using the NIST MultiCal software [10] such that the reference planes are directly at the ports of the antennas. In the case of the dual-polarized antenna, the orthogonal port was terminated in a 50 $\Omega$ Nickel-Chrome thin-film resistor.

Figure 2 compares the measured input impedances for a single-polarized slot-ring (a=228 $\mu$m, 2w=20 $\mu$m) and a dual-polarized slot-ring (a=234 $\mu$m, 2w=20 $\mu$m) with the moment method results. Both the single- and dual-polarized antenna input impedances agree well with the moment method analysis of the single-polarized slot-ring; the moment method analysis does not predict the dual-polarized slot-ring input impedance as accurately. The measured resonant impedances were 120 $\Omega$ at 92.6 GHz for the single-polarized antenna and 112 $\Omega$ at 90.6 GHz for the dual-polarized antenna. The measured antenna resonant frequencies deviate from 94 GHz primarily due to errors in the assumed value of $\epsilon_{eff}$. A test structure was also fabricated to allow measurement of the port-to-port isolation of the dual-polarized slot-ring. The measured and simulated $S_{21}$ of this structure is shown in Figure 3. The fabricated antenna gives better than -25 dB port-to-port isolation from 86-92 GHz.

[1]Stycast HiK is a product of Emerson and Cuming, Inc., Canton, MA.

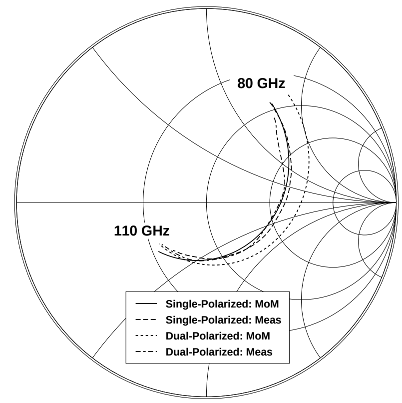


Fig. 2. Simulated (method-of-moments) and measured input impedances of single- and dual-polarized slot-ring antennas from 80-110 GHz.

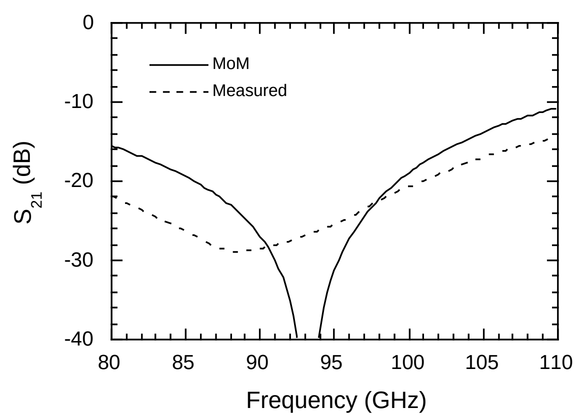


Fig. 3. Simulated (method-of-moments) and measured $S_{21}$ of the dual-polarized slot-ring antenna from 80-110 GHz.

Details of the mixer design are given in [8]. The mixer is based on University of Virginia SC1T7-D20 GaAs antiparallel Schottky diodes. The 38 $\mu$m-thick diode chip is 75 $\mu$m x 195 $\mu$m; the small size of the chip approximates a monolithic geometry while maintaining the flexibility of a hybrid design. The basic circuit (Fig. 1) has a $\lambda_{g,RF}/2$ ($\lambda_{g,LO}/4$) shorted-circuited stub on the LO side of the diode pair such that the diodes are terminated with a short circuit at the RF frequency but the LO signal is not affected. Similarly, a $\lambda_{g,LO}/4$ ($\lambda_{g,RF}/2$) open-circuited stub is located on the RF side of the diode pair such that the diodes are terminated with an open-circuit at the LO frequency but the RF signal is not affected. The IF signal is extracted from the RF side of the diode pair. An open-circuited $\lambda_{g,RF}/4$ stub located $\lambda_{g,RF}/4$ away from the diodes in the IF output circuit acts as an RF choke. A simple single-stub LO matching network is utilized at the LO port.

The antenna is connected to the mixer by a $\lambda_{g,RF}$

section of 50 Ω CPW line, moving the mixer circuitry away from the antenna by roughly one $\lambda_d$. The back-to-back bend in the CPW line is necessary for future integration of four receivers in a 2x2 array for monopulse radar applications. The measured loss of the feedline is 1.2-1.5 dB from 85-100 GHz. This is followed by an 80° at 94 GHz section of 35 Ω CPW line which was optimized to provide the best conjugate match between the predicted mixer RF input impedance and the antenna input impedance over the 92-96 GHz range.

## III. Fabrication and Measurement

The single-polarized receiver (Fig. 4) was fabricated with probe pads at the LO and IF ports to accommodate on-wafer testing with 150 $\mu$m-pitch probes. The probe pad to CPW line transition is identical to that of the TRL calibration standards fabricated on the same die. The receiver size excluding probe pads and transitions is 0.8 mm x 3.8 mm. Airbridges are included at various points in the circuit, particularly junctions, to suppress excitation of the undesired slotline (even) mode in the CPW line. The circuit was fabricated on 535 $\mu$m-thick high-resistivity (>2000 Ω·cm) silicon with a 2800 Å PECVD-grown $Si_xN_y$ layer which is subsequently etched from the CPW gaps [8].

The CPW center conductors and ground planes are 1.3 $\mu$m thick evaporated Ti/Al/Ti/Au, which corresponds to 5 skin-depths at 94 GHz, and 3.5 skin-depths at 45.5 GHz. The 24 $\mu$m wide airbridges are electroplated gold 3 $\mu$m thick at a height of 3.5 $\mu$m above the CPW line. The antiparallel diode chip is mounted using flip-chip technology and bonded to the circuit using EPO-TEK H20E silver epoxy[2]. The design can readily be extended to a fully monolithic implementation.

Noise temperature and conversion loss measurements were performed using the Y-factor method and the measurement setup shown in Figure 5. Microwave absorber (ECCOSORB VHP-2-NRL)[3] at room temperature (290 K) or immersed in liquid nitrogen (77 K) provided the hot/cold load. Based on past experience with this type of measurement a cold temperature of 85 K is used in the Y-factor calculations since the absorber is not a perfect black body radiator. The LO source is a 42-46 GHz mechanically tuned Gunn diode oscillator; the power is varied using a WR-19 level-set attenuator and delivered to the mixer via a 67 GHz Picoprobe[4]. The IF signal is extracted by a second probe connected to a 1.4 GHz IF chain with a gain of 92.5 dB, noise temperature of 40 K, and a bandwidth of 50 MHz. The first stage of the IF chain is an isolator which directs any IF reflection to a cold termination. LO/IF cable, probe, and transition losses are deembedded from the measured data. The measurements represent the conversion loss/noise temperature from a hypothetical plane at the lens surface to the IF port reference plane, and the LO power is defined at the LO port reference plane (see Fig. 4). Coarse lens alignment was performed while operating the receiver as a video detector and shining a 90 GHz plane wave on the aperture. However, with this measurement set-up it was difficult to exactly align the lens with the feed antenna resulting in an increase in the reflection loss.

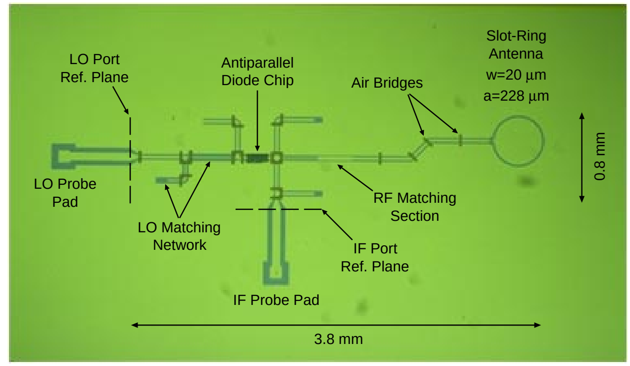


Fig. 4. Photograph of the fabricated single-polarized slot-ring receiver. The total size of the receiver channel excluding probe pads and transitions is 0.8 mm x 3.8 mm. The size of the 38 $\mu$m-thick diode chip is 75 $\mu$m x 195 $\mu$m.

The measured DSB receiver noise temperature is 4300 K at an LO frequency of 45.0 GHz and an IF frequency of 1.4 GHz. The corresponding DSB receiver conversion loss is 12.2 dB. This includes lens reflection and absorption losses, backside radiation, and RF feedline loss. A breakdown of these losses at an RF of 91 GHz are given in Table I. Figure 6 compares the measured DSB noise temperature and conversion loss at an LO frequency of 45.5 GHz and an IF of 1.4 GHz for the single-polarized slot-ring receiver and the uniplanar subharmonic mixer [8] with front-end losses of 0, 4.3, 6.5, and 7.5 dB. It can be seen that the mixer with 6.5-7.5 dB of RF loss will have similar performance to the measured receiver, which is 2-3 dB greater than the estimated total loss. It should be noted that the LO matching network results in broader LO power performance as expected. An RF mismatch between the slot-ring input impedance of $125 + j17$ Ω and the diode RF impedance of approximately 30 - j45 Ω results in 3.2 dB of loss resulting in a total loss of 7.5-7.7 dB. Clearly the 35 Ω RF matching section does not provide the required matching.

[2]EPO-TEK H20E is a product of Epoxy Technology, Inc., Billerica, MA.

[3]ECCOSORB VHP-2-NRL is aproduct of Emerson and Cuming, Canton, MA.

[4]Picoprobe is a product of GGB Industries, Inc., Naples, FL.

TABLE I
Slot-Ring Receiver Antenna and RF Feedline Loss Mechanisms at 91 GHz, 24 mm Si Lens, L = 4400 $\mu$m

| | |
|---|---|
| Calculated Lens Reflection Loss | 2.7 dB |
| Estimated Lens Absorption Loss | 0.2-0.4 dB |
| Calculated Backside Radiation | 0.2 dB |
| Measured RF Feedline Loss | 1.2 dB |
| Total | 4.3-4.5 dB |

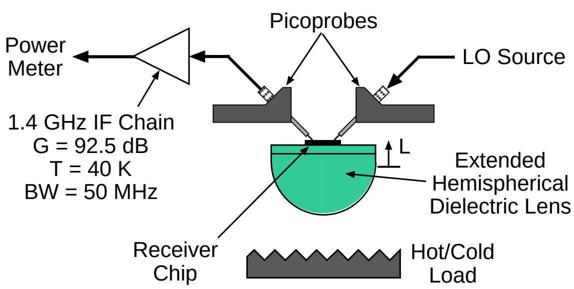


Fig. 5. Measurement setup for measuring the DSB conversion loss and noise temperature of the receiver using the Y-factor method.

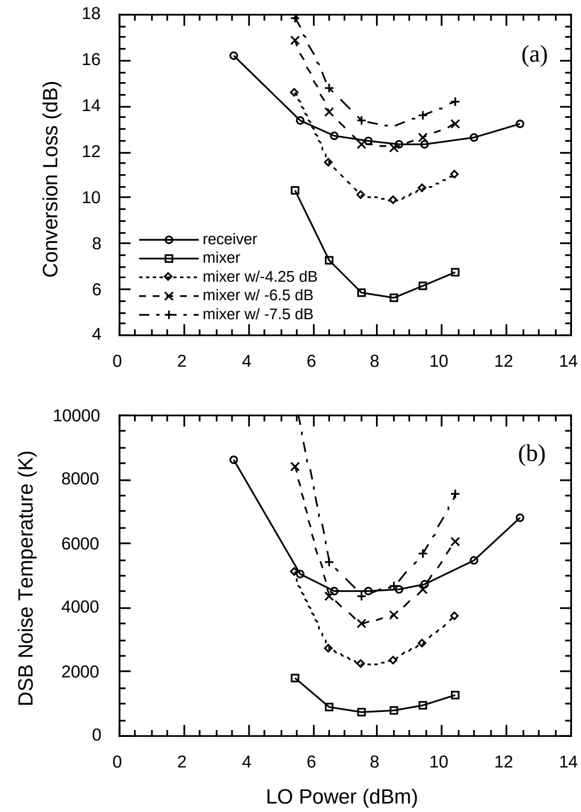


Fig. 6. Measured DSB (a) conversion loss and (b) noise temperature for the single-polarized slot-ring receiver compared with measured results for the uniplanar subharmonic mixer alone with front-end losses of 0, 4.25, 6.5, and 7.5 dB, at an LO frequency of 45.5 GHz and an IF of 1.4 GHz.

With the incorporation of an optimal matching cap layer, the front-end loss can be reduced by 1.5 dB. With an improved RF matching network the loss can be reduced by an additional 2.0-2.5 dB. This should result in a DSB receiver noise temperature of 1700-1900 K and a conversion loss of 8-9 dB. Another option is the incorporation of a W-band MMIC LNA after the antenna, at the expense of increased complexity and cost.

Current work at the University of Michigan is focused on integrating the millimeter-wave receiver chip with an LO/IF distribution network. Single- and dual-polarized receivers designed with transitions to V-connectors (LO) and SMA connectors (IF) have been fabricated on the same die but not yet tested. The antenna patterns and noise performance of these receivers will be reported at the conference. Future work includes fabrication and testing of 2 x 2 arrays of these receivers for both fixed polarization and fully polarimetric monopulse tracking radars.

## Acknowledgments

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