A Uniplanar 90-GHz Schottky-Diode Millimeter-Wave Receiver

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***Abstract*—A 90-GHz Schottky-diode receiver based on a double-slot antenna fed by a coplanar-waveguide (CPW) transmission line is presented. The double-slot antenna is placed on an extended hemispherical high-resistivity silicon substrate lens. The uniplanar receiver results in a 9.3 ± 0.3 dB measured SSB conversion loss at 88–90 GHz including antenna and IF circuit losses and a 1-dB loss due to the use of a nonoptimal matching cap layer at the silicon lens-air interface. The calculated conversion loss agrees very well with the RF measurements. The uniplanar double-slot antenna receiver is very small, less than 1.1 × 4 mm including the RF/IF filter, and is compatible with monolithic two- and three-terminal devices on GaAs substrates. The application areas are in millimeter-wave receivers for automotive systems, communication systems, and radiometric linear imaging arrays.**

I. Introduction

Integrated-circuit receivers consisting of a planar antenna integrated with a matching network and a planar Schottky-diode or a three-terminal device offer an attractive advantage over the waveguide-based receivers at millimeter-wave frequencies. They are smaller, lighter, and less expensive to build than waveguide systems and can be easily produced in large numbers for low-cost applications and millimeter-wave imaging systems. A candidate for a potential of excellent millimeter-wave performance is the double-slot antenna. This antenna was proposed by Kerr *et al.* [1] and later used in conjunction with a hyperhemispherical quartz substrate lens in an SIS receiver at 492 GHz [2]. The double-slot antenna approach has also been used with thick dielectric substrates to cancel the power loss to the dominant TM_0 mode [3], [4]. We have improved the design by: 1) using a coplanar-waveguide (CPW) transmission-line between the slot antennas instead of a microstrip line and 2) placing the slot antenna on an extended hemispherical high-resistivity silicon (or GaAs) substrate lens to result in high gain patterns and high Gaussian coupling efficiency [5], [6]. The CPW ground-planes are equalized using air-bridge technology and the design requires no via holes or a backing ground-plane. The uniplanar design is compatible with monolithic integration of state-of-the-art Schottky-diodes and high-speed transistors. This results in planar receivers for millimeter and submillimeter-wave systems.

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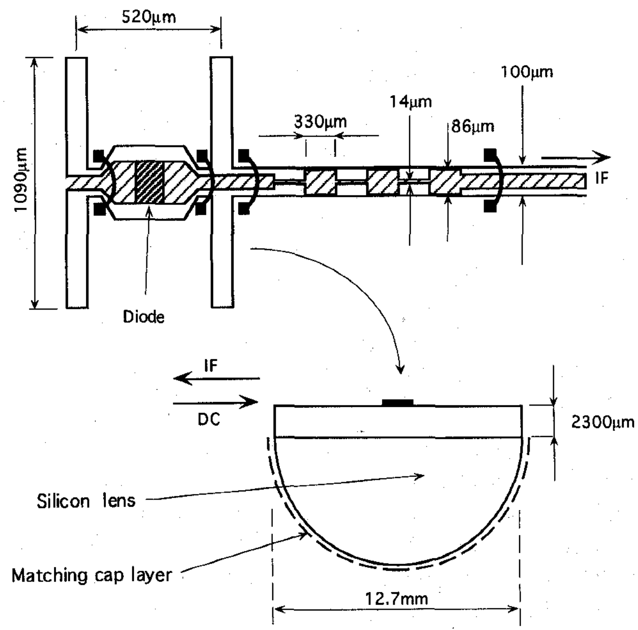

Fig. 1. Layout of the 90-GHz CPW-fed double-slot antenna.

II. Antenna Design

The CPW-fed double-slot antenna receiver is shown in Fig. 1. In this design, the length of the slot antenna controls the H-plane pattern and the separation between the slot antennas controls the E-plane pattern. The patterns are calculated assuming a sinusoidal magnetic current distribution on the slot-antenna and using an array-factor in the E-plane direction. The wavelength of the sinusoidal current distribution in the slot is the guided wavelength given by $\lambda_g = \lambda_0/\sqrt{\epsilon_g}$ with $\epsilon_g = (1+\epsilon_r)/2$ and $\epsilon_r = 11.7$ for high resistivity silicon [6], [7]. The slot antennas are chosen to be 0.28 λ_0-long with a separation of 0.14 λ_0, where λ_0 is the free-space wavelength at 90 GHz ($\lambda_0 = 3.33$ mm). This results in a symmetrical pattern with a 10-dB beamwidth around 48° and an associated directivity of 11 dB inside the silicon dielectric lens. The calculated cross-polarization level is lower than −30 dB in the 45°-plane. The dielectric lens approach eliminates the power loss to substrate modes and makes the pattern unidirectional into the dielectric lens [9]. The power radiated to the back-side is minimal, only 9% (0.4 dB), and therefore no back-cavity is used to recover this power loss.

The far-field pattern of the double-slot antenna/extended hemispherical lens system is calculated using a ray-tracing technique inside the silicon lens and aperture field integration

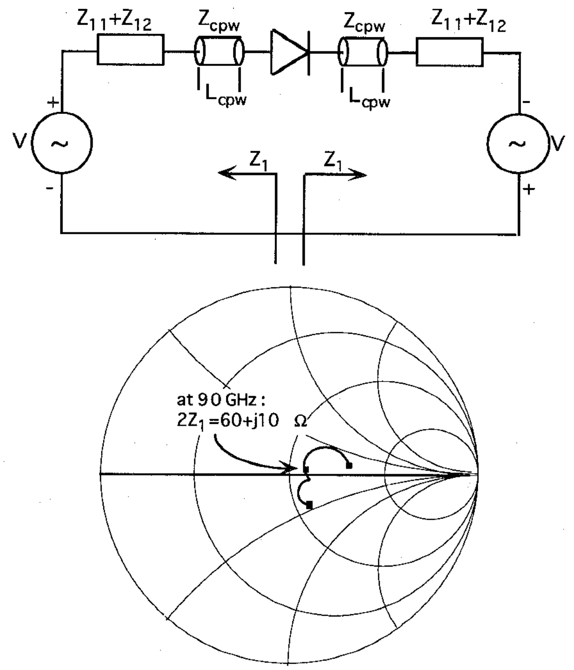

Fig. 2. The impedance environment of the Schottky diode and the measured values on a 2-GHz model over a ±5% frequency range.

on the silicon-lens contour. For a complete description of this method, the reader is referred to the work of Filipovic *et al.* [5]. The double-slot antenna is placed at an extension length of 2300 μm ($L/R = 0.33$) behind the hemispherical center of the lens. This results in a directivity of 22 dB and a 91% Gaussian-coupling efficiency. The Gaussian-coupling efficiency does not include power loss to the back-side (0.4 dB) and the reflection loss at the silicon-air interface. The reflection loss is calculated to be 1.7 dB for no matching-cap layer on the silicon lens and 0.2 dB for a $\lambda_m/4$ matching-cap layer with uniform thickness [5], where λ_m is the mean wavelength between silicon and air and is given by $\lambda_m = \sqrt{\lambda_0 \lambda_{Si}}$. It is important to note that a high directivity and a Gaussian coupling efficiency of 88% is also achieved if the double-slot antenna is placed on an elliptical silicon lens [5].

III. Receiver Design

The Schottky-diode is placed in series between the slot antennas to result in a sum-mode pattern (Fig. 1). The CPW line dimensions are $s = 50\,\mu$m and $w = 25\,\mu$m at the slot-antenna feed-points resulting in a line impedance of 50 Ω on a semi-infinite silicon substrate. The ground-planes of the CPW line are equalized using air-bridges just near the feed-points of the slot-antennas. The CPW is widened in the middle so as to accommodate a planar (hybrid) Schottky-diode. The planar diode is an Alpha 32654 and is silver-epoxied to the CPW line. The CPW line is short-circuited to the ground-plane at the left slot antenna and this provides the dc return for biasing the diode. On the right slot-antenna, the CPW line is connected to a low-pass IF filter. The IF filter presents a short-circuit at the slot antenna input at 90 GHz. The slot antenna self and mutual impedances on an infinite dielectric have been calculated recently [2], [7], and the second resonance ($0.28\lambda_0$-long antenna) provides a wideband self impedance

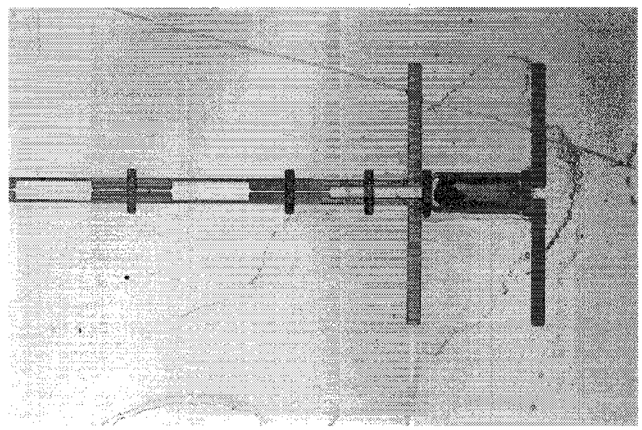

Fig. 3. The fabricated 90-GHz receiver. For dimensions, see layout in Fig. 1.

(Z_{11}), around 30 Ω, on silicon substrates. The impedance at the diode terminals is given by a series combination of the slot antenna input impedance as seen in Fig. 2. However, in this case, Z_1 is difficult to calculate due to the widening geometry of the CPW line and the relatively large GaAs substrate of the hybrid Schottky-diode (400 × 130 μm). A 2-GHz model was built and the *measured* input impedance at the diode terminals is $60 + j10$ Ω (Fig. 2). This was done by using an appropriate Balun, and by using a small piece of Stycast [8] over the CPW transmission line to model the effect of the hybrid GaAs diode. The 2-GHz model was placed on a large Stycast block ($\epsilon_r = 12$) surrounded by an RF absorber and time gating was used to eliminate the reflections from the Stycast-absorber interface. The measured input impedance at the second harmonic is $17+j14$ Ω. Both measured impedances have a comfortable ±5% bandwidth.

The nominal diode capacitances are $C_{j0} = 18$ fF and $C_p = 14$ fF and the measured dc parameters are $R_s = 8$ Ω, $n = 1.1$, $\Phi_b = 0.78$ V and $I_s = 1.6 \times 10^{-14}$ A. This yields a figure-of-merit cutoff frequency given by $f_T = 1/2\pi R_s(C_{j0} + C_p)$ of 620 GHz. The mixer theoretical SSB conversion loss [10], [11] is calculated to be 7.0 ± 0.1 dB at an LO frequency of 90 GHz, an IF frequency of 1.4 GHz, a dc bias of 0.5 V, a dc current of 3 mA, and an available LO power at the diode terminals of 2–3 mW. The calculated diode impedance is $37 - j30$ Ω and the RF mismatch between the antenna and the diode is around 1.5 dB. The calculated output IF impedance is 70–75 Ω.

The IF network consists of a 7-section low-pass CPW filter with a corner frequency of 53 GHz and a short-circuit rejection of −24 dB at 90 GHz. The filter is of alternating low (27 Ω) and high (78 Ω) impedance sections and the corresponding CPW geometry is obtained from LineCalc [12]. The IF filter is 3.5 mm long with a measured DC series resistance of 6 Ω. The filter is followed by a $\lambda/4$ microstrip matching network at 1.4 GHz on a low-loss Duroid Substrate [13] with an impedance of 60 Ω.

IV. Millimeter-Wave Measurements

The receiver was built using standard photolitographic techniques for 86–94 GHz operation on a high resistivity silicon substrate (2000 Ω−cm,). The antennas and CPW lines are evaporated gold 5000–6000 Å thick, and the air-bridges are fabricated using an electroplating technique (Fig. 3). The

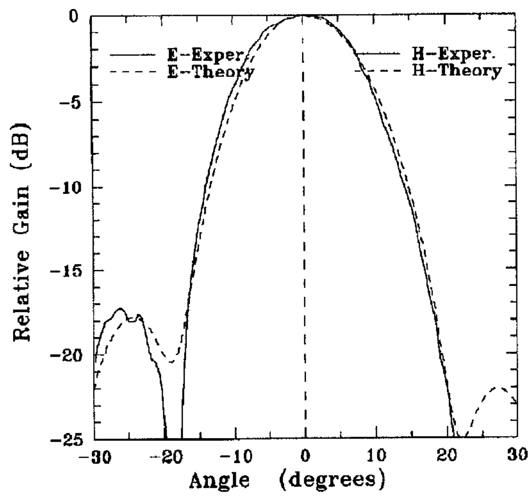

Fig. 4. Measured and calculated E- and H-plane patterns at 88 GHz.

air-bridges are 1–1.2 μm thick, 15 μm wide, 100 μm long and with a height of 1.4 μm over the CPW transmission line. The planar diode is hybrid mounted on the CPW line using silver epoxy. It is possible to build an identical receiver monolithically on a GaAs substrate with a planar millimeter-wave Schottky-diode [14].

The double-slot antenna was centered on a 12.7-mm-diameter extended hemispherical silicon lens. Fig. 4 shows the measured patterns at 88 GHz. The E- and H-plane patterns are symmetrical with low sidelobe levels, possess a high Gaussian coupling efficiency, and agree very well with theory. The measured cross-polarization level is below −25 dB in the 45° plane. The *forward* pattern directivity is calculated to be 22.3 ± 0.2 dB at 94 GHz and 21.3 ± 0.2 dB at 88 GHz by averaging the measured E, H, and 45°-plane patterns (not shown for 94 GHz). The calculated *forward* directivity neglects the radiated power behind the lens and agrees quite well with the theoretical forward directivity [5]. This results in an aperture efficiency (coupling to a plane wave) of 85 ± 4% at 94 GHz for a 12.7-mm-diameter silicon lens. The system video responsivity is defined as the measured low frequency voltage in a 120 KΩ load divided by the total 94-GHz RF power incident on the 12.7 mm lens aperture (see [14] for more detail). The measurements show a high system video responsivity (800 ± 40 V/W) at a bias current of 20 μA (no matching-cap layer was used) due to the good RF match between the double-slot antenna and the planar diode. The video responsivity referenced to the diode terminals can be calculated by normalizing out the antenna loss and is 1600 V/W.

With this design, it is possible to inject the local oscillator from the back side of the silicon lens. The penalty paid is a 90% loss of the available LO power since the double-slot antenna radiates most of its power into the dielectric lens. We have chosen to use a high-performance quasi-optical setup to inject the LO with minimal loss. The quasi-optical setup is done using a Martin-Pupplett (MP) interferometer at an IF frequency of 1.4 GHz (Fig. 5). The quasi-optical system is optimized at each measurement frequency by tuning the MP interferometer and slightly changing the distances between the

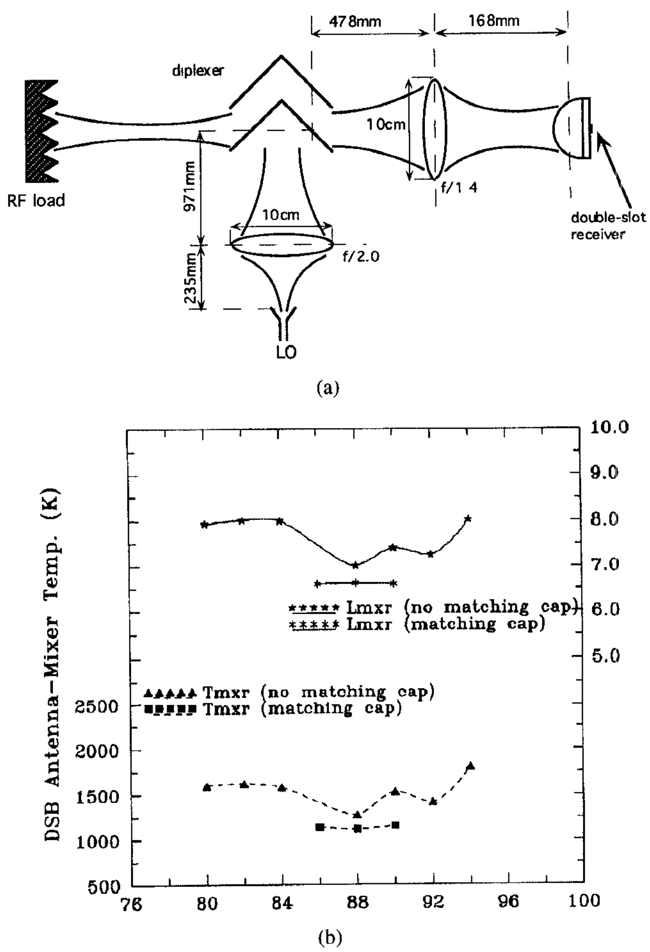

Fig. 5. The 90-GHz millimeter-wave measurement setup (a) and the measured DSB receiver conversion loss and noise temperature (b).

silicon lens and the $f/1.4$ objective lens. The IF chain is composed of a circulator with a cooled load at the isolated port, a bias-T, and low-noise amplifiers. The IF chain has a gain of 98.6 dB and a noise-temperature of 94 K with a bandwidth of 100 MHz. The reader is referred to [15] for a detailed description on the calculation of the antenna-mixer performance.

The measured DSB conversion loss and noise temperature are presented in Fig. 5. The reflection and absorption loss (estimated at 0.45 and 0.25 dB, respectively) of the 10 cm $f/1.4$ Rexolite objective lens have been normalized out of the measurements. The measured IF reflection is 0.2–0.3 dB and is also normalized out of the measurements [15]. A DSB conversion loss and noise temperature of the antenna-mixer of 7.0 ± 0.3dB and 1300 ±50K is measured without a matching cap layer at 88–90 GHz. The DSB performance improved to 6.3 ± 0.3 dB and 1000 ± 50K with a nonoptimum matching cap layer. The DSB mesurements include the antenna loss to the backside (0.4 dB), the antenna Gaussian coupling efficiency (0.4 dB), the silicon lens absorption loss (0.1–0.2 dB), the lens-air reflection loss (see below), the diode conversion loss, and the IF-filter ohmic loss. The nonoptimal matching cap-layer improved the conversion loss by 0.7 ± 0.1 dB instead of 1.5 dB due to the incorrect thickness used. Therefore, a residual lens-air reflection loss of 1.0 ± 0.1 dB is part of

TABLE I
A DETAILED BREAKDOWN OF THE LOSS MECHANISM AND COMPARISON WITH MEASURED RESULTS AT 90 GHz

Antenna	
Calculated Back-Side Power Loss	0.4 dB
Calculated Gaussian Coupling Efficiency	0.4 dB
Estimated Lens Absorption Loss	0.1-0.2 dB
Residual Lens-Air Reflection Loss	1.0 dB*
*Can be reduced to 0 2 dB with quarter wavelength matching layer.	
Mixer	
Calculated SSB Diode Conversion Loss	5.5 dB
RF Mismatch between Diode and Antenna	1.5 dB*
*Can be eliminated with better impedance design	
IF Section	
Calculated IF-Filter Ohmic Loss	0.4 dB*
*Can be eliminated with shorter IF filters.	
Total Calculated SSB Conversion Loss	9.3-9.4 dB
Measured SSB Conversion Loss	9.3±0.3 dB

the measured performance at 86–90 GHz with a nonoptimal matching cap-layer.

The best performance was achieved for a dc bias of 0.73 V and a dc current of 2.4 mA. The available optimal LO power at the lens aperture is 5–7 mW. The available LO power at the diode terminals is 3–4 mW after taking into account the total antenna loss. These values are in good agreement with the harmonic balance results. A detailed loss breakdown is given in Table I. It is seen that the measured performance agrees very well with theory. The IF-filter ohmic loss (0.4 dB) is due to the 6Ω series resistance in the 70Ω IF circuit and can be eliminated in future designs. The silicon-lens/air reflection loss can be reduced to 0.2 dB with the use of a correct matching-cap layer. It is seen that the double-slot antenna on a silicon dielectric lens contributes only 1.2 dB of losses to the overall system performance when the correct matching cap layer is used. The quasi-optical double-slot antenna receiver could therefore result in 6.7-dB SSB conversion loss systems. This is competitive with the best available millimeter-wave waveguide receivers at a fraction of the cost.

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Thomas P. Budka, photograph and biography not available at the time of publication.

Daniel F. Filipovic, photograph and biography not available at the time of publication.

Gabriel M. Rebeiz (SM'93), photograph and biography not available at the time of publication.