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A 140-170 GHz Low-Noise Uniplanar Subharmonic Schottky-Receiver

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Abstract

A 150 GHz Schottky-diode subharmonic receiver based on a coplanar-waveguide (CPW) fed double folded-slot antenna is presented. The double folded-slot antenna is placed on an extended hemispherical high-resistivity silicon substrate lens to achieve a high directivity and a high coupling to a Gaussian beam efficiency. The uniplanar receiver results in a 12±0.5 dB measured DSB conversion loss at 144-152 GHz for a 8-10 mW LO power at 77 GHz, and has a wideband $\leq$13 dB conversion loss over 30 GHz of bandwidth (140-170 GHz). The measured conversion loss includes silicon lens absorption and reflection losses, as well as IF mismatch losses. The applications are in new small aperture (7.5 cm lenses) collision avoidance radars at 150 GHz.

I. INTRODUCTION

Automotive electronic applications require light, small and low-cost circuits at millimeter-wave frequencies. The current design frequency for automotive systems is 77 GHz in Europe and other countries (such as USA). The far-field beamwidth of an antenna is given by the aperture size and is proportinal to λ/D, where D is the aperture diameter. Therefore, at this frequency, 15 cm lenses are required to achieve the appropriate resolution at 100 m (1.5^o 3-dB beamwidth). If 154 GHz is used, then the same beamwidth can be achieved using a

7.5 cm lens (Fig. 1). This would make the automotive radar smaller and more practical for modern automobiles.

Integrated-circuit uniplanar receivers consisting of planar antennas, matching networks and mixers often rely on coplanar waveguide (CPW) technology and offer many advantages over waveguide-based systems. The designs are low-cost and easy to fabricate, especially at millimeter-wave frequencies. Two planar CPW-fed antennas have been used commonly in integrated millimeter-wave receivers. The double-slot antenna has been demonstrated in a 94 GHz fundamental Schottky-receiver [1] but the antenna geometry does not allow for RF amplification before downconversion. The slot-ring antenna has been used in a W-band integrated monopulse radar receiver based on a subharmonic mixer [2], and is an attractive candidate for array applications due to its compact size. However, the slot-ring antenna has a relatively high input impedance (100-120 Ω) and is not suitable for low impedance Schottky-diode receivers. In this work, a 150 GHz uniplanar subharmonic Schottky-diode receiver is developed relying on the double folded-slot antenna which has a low input impedance [3, 4]. The design follows earlier work done by Raman et al. [5], but in an integrated antenna-mixer structure [6, 7]. This is different than waveguide based subharmonic mixers which provide excellent performances up to 600 GHz [8, 9]. In this case, the LO is injected on-wafer, resulting in a simple and compact receiver. The design is compatible with monolithic integration of state-of-the-art Schottky-diodes and high-speed transistors, for millimeter automotive systems.

II. RECEIVER DESIGN

A. DIODE

The subharmonic receiver is based on the University of Virginia Schottky diode SC1T7-D20, and consists of two back-to-back diode junctions with very low junction and parasitic capacitances (C_{j0}=2.5 fF, C_p=11 fF). The DC parameters are deduced by curve fitting from the measured IV curve and are R_s=6.5 Ω, n=1.163, Φ_b=0.842, γ=0.5, and $I_0 = 4 \times 10^{-14}$ A, resulting in a figure-of-merit cutoff frequency of $f_c = 1/2\pi R_s(C_{j0} + C_p)$=1.8 THz. The RF, LO and IF input impedances of the back-to-back diodes are simulated using an adapted version of Kerr's subharmonic mixer analysis [10] and are: Z_{RF}=22-j30 Ω, Z_{LO}=37-j100 Ω, and Z_{IF}=120 Ω at a RF of 154.2 GHz, an LO of 77 GHz and an IF of 0.2 GHz, respectively. The minimum DSB conversion loss for such a diode is simulated to be 5.5-6.0 dB at a 8-10 mW LO power, over the 150-154 GHz range. However, with R_s=6.5 Ω due to the skin resistance, the diode series resistance is expected to be around 10-12 Ω at 150 GHz, resulting in a DSB conversion loss of 7-8 dB.

B. DOUBLE FOLDED-SLOT ANTENNA

The double folded-slot (DFS) antenna is an array of two folded-slot antennas (Fig. 2) placed approximately ($\lambda_d/2$) apart. Each folded-slot antenna acts like a $\lambda_g/2$-long folded CPW line. The wavelengths λ_d and λ_g are the dielectric and guided wavelengths, respectively. The two folded-slot antennas are fed in phase using a $\lambda_g/2$-long (180^o-long) CPW line, resulting in symmetrical radiation patterns in the broadside direction, and low cross-polarization levels ($\leq$ -23 dB) [3, 4]. However, the physical separation is ($\lambda_d/2$) for good radiation patterns in the dielectric, and is therefore shorter than the $\lambda_g/2$ feed line. This problem is easily solved by bending the $\lambda_g/2$ feed line as shown in Fig. 2.

The 150 GHz double-folded slot antenna is 380 μm long ($0.5\lambda_g$ or 180^0 at 154 GHz), with a separation of 320 μm ($0.4\lambda_g$), based on Momentum [11] simulations. The input impedance of the DFS antenna has been measured on a scaled version of the antenna at 70-110 GHz and compared with Momentum simulations (Fig. 3). The results indicate that the DFS antenna has a very wide impedance bandwidth with a relatively low input impedance of 20 Ω at 94 GHz (corresponding to 154 GHz), which is a very good match to the diode RF impedance (22-j30 Ω). Furthermore, the DFS antenna is a DC open circuit, and no DC filter is needed in the RF port to block the DC bias component of the diode.

The far-field radiation patterns of the double folded-slot antenna placed nearly at the elliptical position of a 12.7 mm diameter silicon lens are measured at 150-154 GHz. The measured E- and H-plane patterns at 150 GHz and 154 GHz are shown in Fig. 4. The patterns are symmetrical even with the presence of small amounts of spurious radiation down to the -17 dB level, attributed to the CPW feed line and CPW stubs in the RF circuit. The -3 dB and -10 dB beamwidths are 8^o and 15^o at 154 GHz, resulting in a co-polarized directivity of 27.2±0.2 dB, calculated by averaging the measured E and H-plane patterns, and a maximum aperture efficiency of 92±3%. The sidelobe levels remain below -15 dB at 150-154 GHz and the measured cross-polarization levels in the E- and H-planes are below -25 dB. The 10 dB beamwidth of 15^o is given by the silicon lens (12.7 mm diameter) which was available for pattern measurements when the DFS antenna is used in a focal plane system the lens diameter should be reduced to 3.2 mm so as to result in a beamwidth of 60^o which is compatible with f1 lens systems. The diameter of the f1 lens should be around 7.5 cm for a 1.5^o beamwidth.

C. MIXER DESIGN

The mixer design is very compact (2×2 mm) and LO and RF matching networks are not included for simplicity. The 70-85 GHz LO signal is injected on-wafer with a W-band picoprobe, and is shorted at the RF port by a 417 μm long ($\lambda_{gLO}/4$) open stub. The RF signal is shorted at the LO port by a 420 μm ($\lambda_{gRF}/2$) long shorted stub. The shorted stub also provides the DC and IF short. The RF choke consists of two 0.2 pF capacitors placed $\lambda_{gRF}/2$ apart in the IF port, resulting in a 10 GHz cut-off frequency (Fig. 5). The 0.1-2.0 GHz IF signal is also extracted on-wafer using a K-band probe. The design takes into account the packaged diode feeding lines which are estimated to be 70^0 (or 35^0) long at the RF (or LO) frequency. The substrate is high resistivity silicon (ϵ_r = 11.7) capped by 2500 Å of Si_3N_4. The Si_3N_4 layer is etched in the CPW lines, resulting in an effective dielectric constant of ϵ_{eff}=6.0 at 77 GHz and 154 GHz. In all cases, the CPW line impedance is 52 Ω (s=24 μm and w=15 μm). The CPW attenuation was measured at 70-110 GHz, and the extrapolated loss at 150 GHz is 0.9 dB/mm.

III. MILLIMETER-WAVE MEASUREMENTS

The receiver is built using standard photolitographic techniques, and the metalization is 6000 Å of evaporated gold (2 skin depths at 150 GHz). The CPW grounds are equalized with electroplated air-bridges (20 μm wide, 3 μm thick), and the Schottky diode is connected to the CPW lines using silver epoxy. The receiver is placed on the back side of a 12.7 mm-diameter extended hemispherical silicon lens. The extension length is 2450 μm to reach an intermediate position, where the coupling to a Gaussian beam is 91%. A $\lambda_m/4$-thick stycast matching-cap layer was used to reduce the silicon lens reflection losses (Fig. 6(a)), where $\lambda_m = \lambda_d/\sqrt{\epsilon_r}$. The IF chain was calibrated at 0.2 GHz and 1.4 GHz, with a gain and noise temperature of 93.8 dB and 110 K, and 93.6 dB and 103 K, respectively.

The subharmonic receiver DSB conversion loss was measured using the hot/cold load method for an IF frequency of 0.2 GHz and 1.4 GHz and are presented in Fig. 6. A receiver DSB conversion loss of 12±0.5 dB is measured at 144-152 GHz, for an available LO power of 8-10 mW at the probe tip (Fig. 7). The conversion loss is close to values obtained in current 77 GHz radar systems. The conversion loss is less than 13 dB at 140-170 GHz, resulting in a 20% bandwidth. The measurement includes the IF mismatch and probe losses (0.3 dB), the backside radiation losses (calculated to be 0.5 dB) and the silicon lens absorption losses (1.1 dB). Also, the CPW attenuation loss between the antenna and the mixer is estimated to be 0.8 dB at 150 GHz. The ripples in the measurements indicate the matching-cap layer is not optimum and the reflection losses at the silicon/air interface are estimated to be 1.0 dB. The total calculated losses are then 10.7 dB DSB including the ohmic losses in the DFS antenna, estimated to be 1.0 dB (due to the small dimensions of the folded slots), but not including the losses of the stubs before and after the diodes. This compares well with the measured 12±0.5 dB DSB conversion loss (Table I).

IV. CONCLUSION

A planar integrated subharmonic receiver has been developed at 140-170 GHz. The receiver shows a wideband DSB conversion loss of 11.5-13.5 dB at 140-170 GHz due to the wideband low input impedance of the antenna (20 Ω), which presents a good match to the subharmonic diode input impedance (22-j30 Ω). The local oscillator can be integrated on-chip at 77 GHz, resulting in a low-cost uniplanar monolithic receiver for future automotive applications.

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[10] Diode Mixer Analysis Program, provided by Prof. S.A. Maas, Private Consultant.

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DFS Antenna and Dielectric Lens	
Calculated Back-Side Power Loss	0.5 dB
Estimated Lens Absorption Loss	1.1 dB
Residual Lens-Air Reflection Loss	1.0 dB
DFS Ohmic Loss	~ 1.0 dB
Mixer	
Calculated DSB Diode Conversion Loss	7-8 dB
RF CPW Attenuation Losses	0.8 dB
IF Section	
IF Probe and Atternuation Losses	0.3 dB
Total Calculated DSB Conversion Loss	11.8-12.8 dB
Measured DSB Conversion Loss	12±0.5 dB

Table I. A detailed breakdown of the loss mechanism and comparison with measured results at 140-170 GHz.

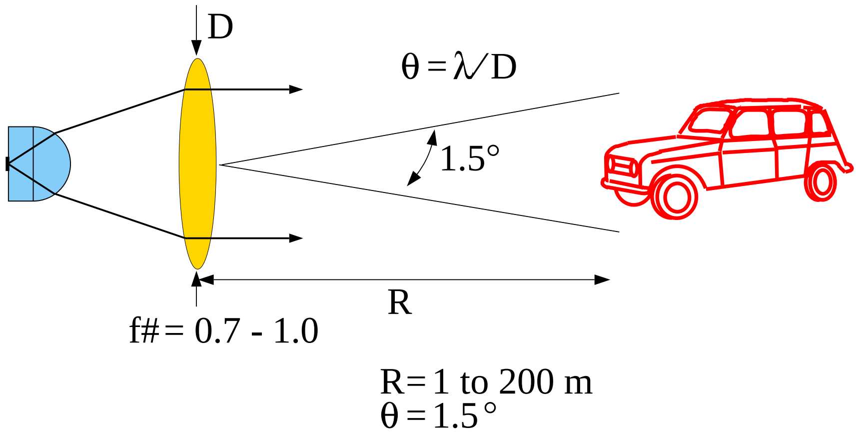


Fig. 1. A radar for automotive applications: a 3-dB beamwidth of 1.5^o is required to resolve a car at 100 m.

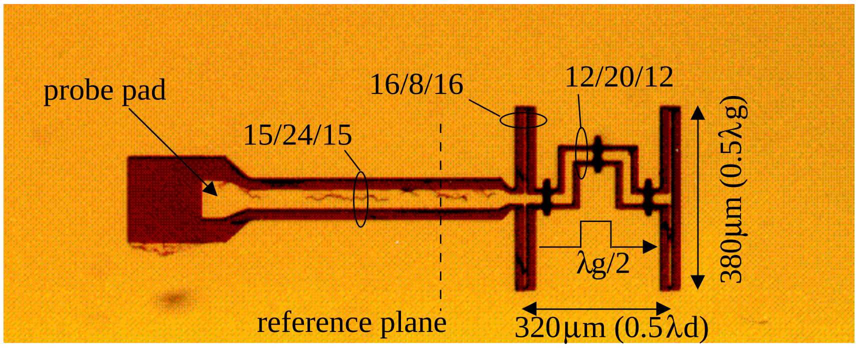


Fig. 2. Picture of the 150 GHz double folded-slot antenna.

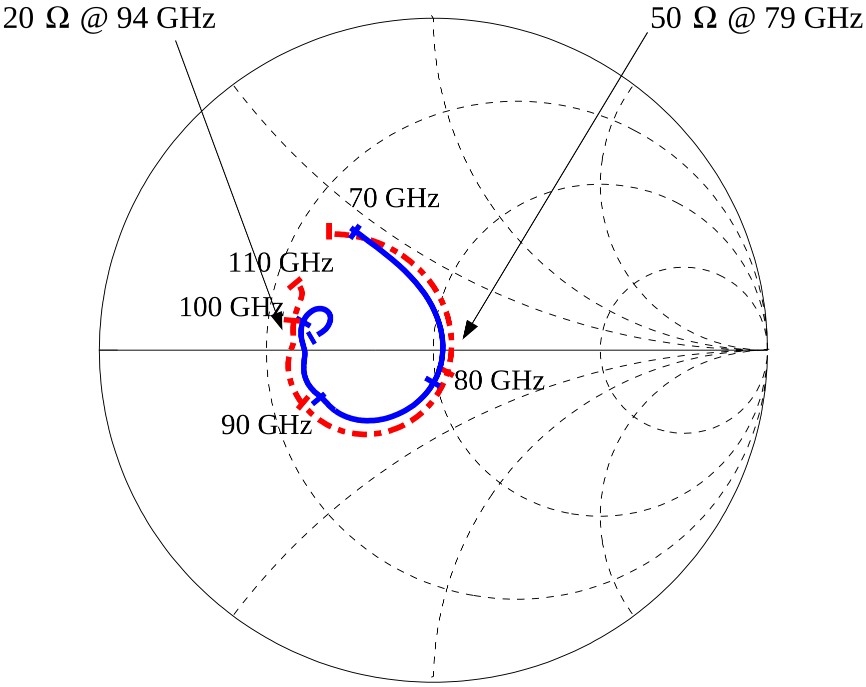
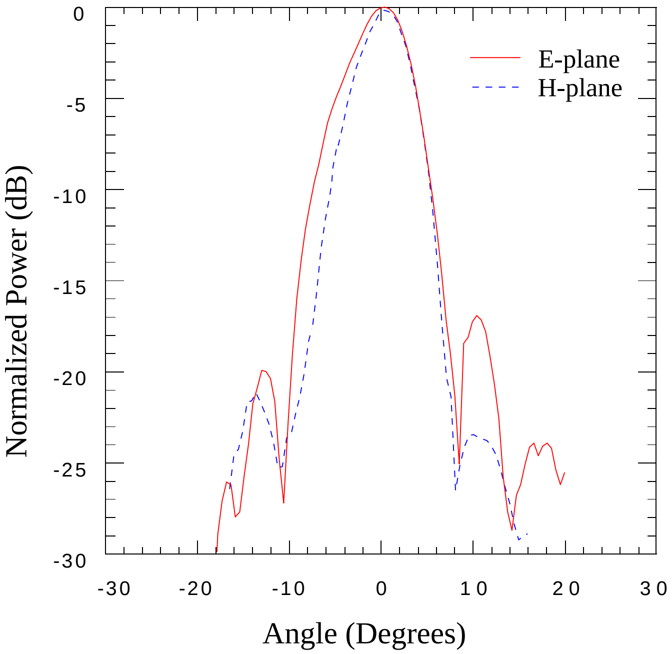
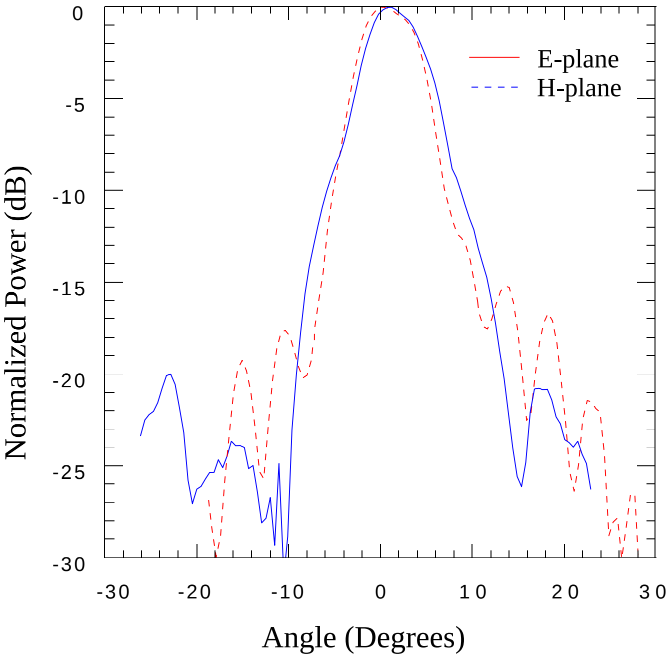


Fig. 3. The measured input impedance of the scaled 70-110 GHz double folded-slot antenna. The input impedance is 20 Ω at 94 GHz.

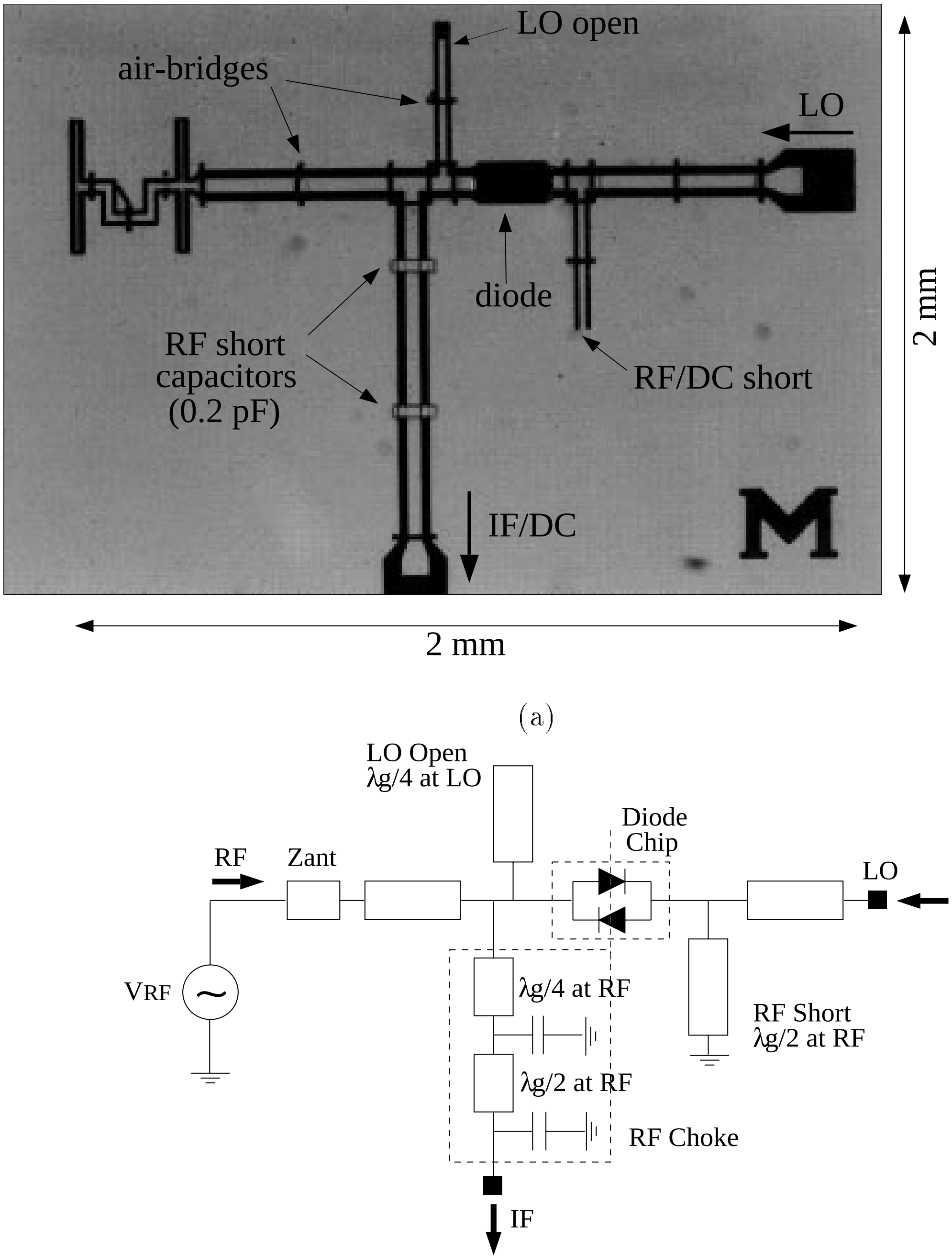


(a)



(b)

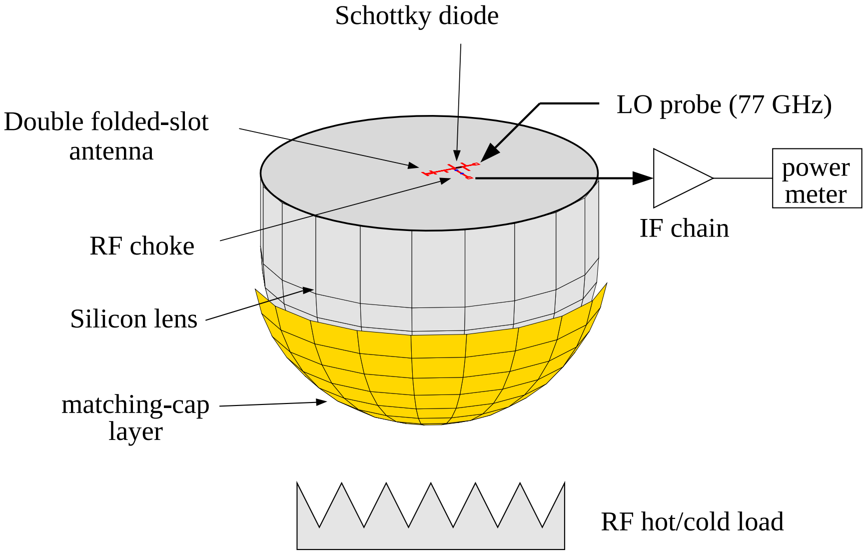
Fig. 4. Double folded-slot antenna radiation patterns measured on a 12.7 mm silicon lens at 150 GHz (a) and 154 GHz (b). The measured cross-polarization levels in the E- and H-planes are below -25 dB.



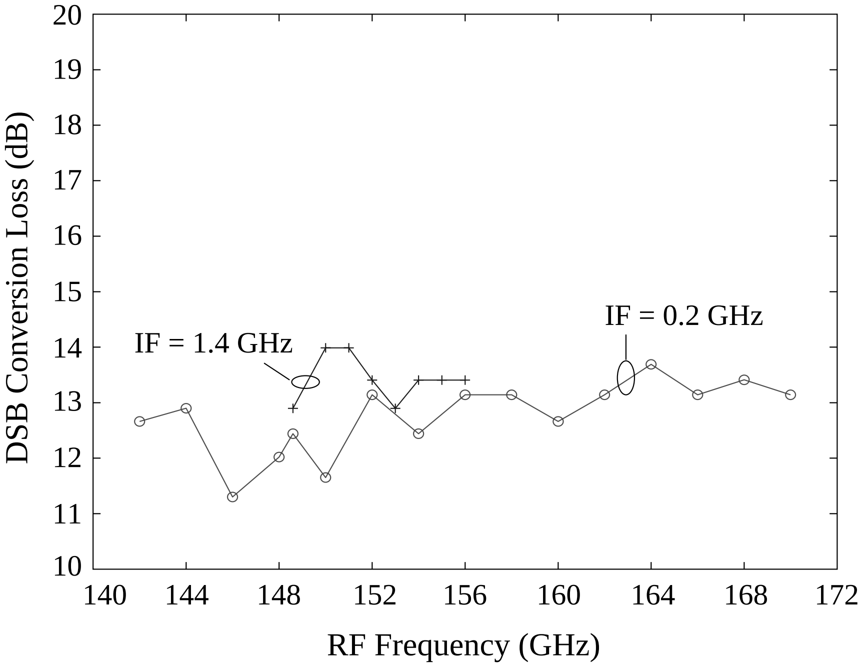
(a)

(b)

Fig. 5. The layout of the subharmonic mixer (a) and impedance environment (b).



(a)



(b)

Fig. 6. Measurement set-up (a) and measured DSB conversion loss at 142-170 GHz for an IF frequency of 0.2 GHz and 1.4 GHz (b).

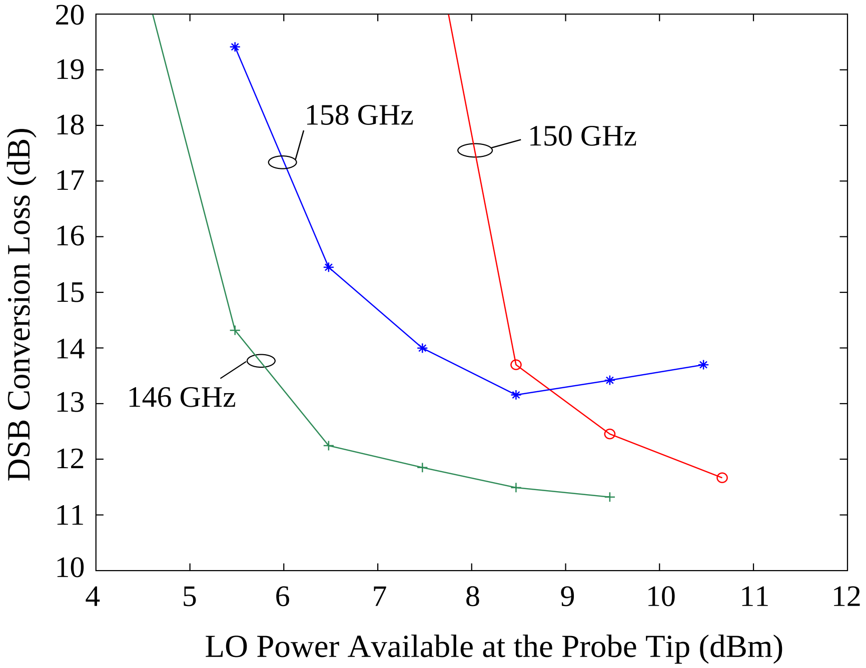


Fig. 7. Measured DSB conversion loss versus LO power available at the probe tip at 146 GHz, 150 GHz and 158 GHz.