A Low VSWR 2SB Schottky Receiver

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***Abstract*—A novel high performance waveguide integrated sideband separating (2SB) Schottky receiver operating in the 320 -360 GHz band is presented. The unique receiver design is based on a core of two subharmonic Schottky diode mixers with embedded LNA's with a minimum noise figure of 1.8 dB, fed by LO and RF quadrature hybrids. At room temperature, a typical receiver SSB noise temperature of 3000 K is measured over most of the band reaching a minimum of 2700 K, with only 4 mW of LO power. The sideband ratio SBR is typically below 15 dB over the whole band and the measured LO input return loss is typically below 15 dB broadband. High performance sideband separating Schottky receivers can now for the first time be considered for submillimeter wave systems enabling new types of instrument concepts.**

***Index Terms*—Submillimeter wave technology, schottky diode, receivers, radiometers, subharmonic mixers, sideband separating mixers, dual sideband receivers, image rejection mixers**

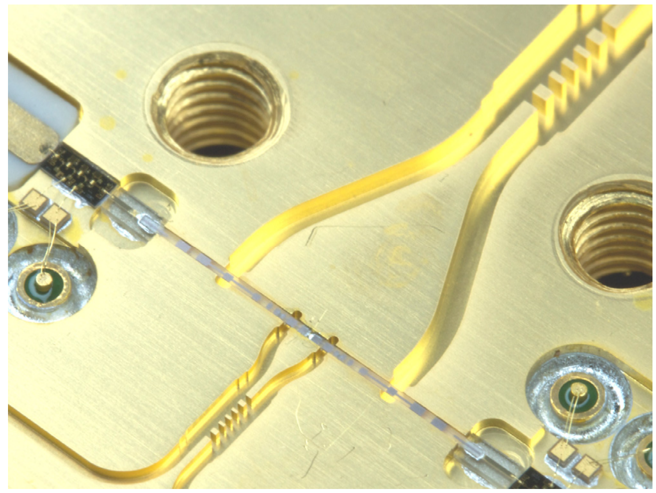

Fig. 1. 2SB receiver assembly showing the RF and LO branch guide couplers, two subharmonic Schottky diode mixers and two MMIC IF LNA's with accompanying bias circuitry and IF connector launchers.

I. Introduction

SIDEBAND separating receivers and image rejection mixers operating in the submillimeter wave regime, with high sideband ratio (SBR) and low noise are needed for radio astronomy and remote sensing applications [1-3]. The ability to separate the receiver upper and lower sidebands and rejection of the image band noise is useful for the reduction of the antenna noise contribution and for the suppression of unwanted image band signals. Looking back, image rejection has been achieved by means of filtering techniques, often implemented as waveguide filters or bulky quasi optical filters, with increased loss and little or no tuning capability. Recent improvements in semiconductor fabrication, circuit processing and high precision machining technology, has led to an increased repeatability and enhanced component performance and made it possible to make integrated sideband separating THz receivers. With the rapid development of novel micro-machining techniques, the performance of these systems is constantly improving and state-of-the-art superconductor-isolator-superconductor (SIS) and hot electron bolometer (HEB), 2SB and balanced receivers [4-6], can now be found operating at frequencies around 1 THz. However, the development of integrated 2SB heterodyne receiver topologies has so far been exclusively done for cryogenic applications, leading to a technological gap for room temperature Schottky diode based applications.

The main difference between cryogenic SIS receivers and room temperature Schottky diode receivers [7-12] is the low noise of SIS receivers for which image rejection levels of 10 dB or higher could largely benefit the system noise performance, reducing the antenna noise almost by a factor of two. For Schottky diode based receiver systems used in atmospheric research, the motivation for using image rejection mixers is somewhat different. For such instruments the receiver noise temperature is often much larger than the antenna noise, which is typically close to the brightness temperature of the sky or earth, and they would therefore not benefit much by the suppression of the image noise. Instead it has been the complex spectral composition and line broadening effects that has been the driving factor for using image rejection techniques. The requirements on

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image rejection also differ and sideband suppression levels of 20 dB or higher are typically needed, often over several octaves of IF bandwidth. Moreover, due to the relative high LO power requirements of Schottky mixers, subharmonic mixers [13], are preferably used for which conventional fundamental 2SB topologies can not be applied.

At lower frequencies various subharmonic 2SB receiver topologies have already been demonstrated [14-17] using different hybrid implementations. For submillimeter wave applications a 45 degree waveguide hybrid topology was first proposed using a stub loaded differential phase shifter [18]. It was later implemented in [19, 20], as a modular receiver and in [21], demonstrating a waveguide integrated 2SB receiver for the first time. A planar version of the 45 degree hybrid, suitable for submillimeter wave applications has also been proposed [22], using simple stepped impedance filters or coupled line filters.

In this paper a novel broadband 2SB receiver topology, that was introduced in [19, 20], with enhanced performance compared to previously proposed topologies, is presented. In the design RF and LO quadrature feeding of two subharmonic double sideband (DSB) mixers is utilized for obtaining a low LO and RF port voltage standing wave ratio (VSWR) and high mixer LO and RF isolation, which in turn minimizes the effect of mismatches to adjacent subsystems and leads to an inherent low ripple performance and high image rejection level.

The topology has been realized as a waveguide integrated subharmonic IQ-receiver module, see Fig. 1, operating in the 320 - 360 GHz band. The design is based on a subharmonic suspended hybrid mixer design, employing discrete planar anti-parallel Schottky diodes [23] from VDI, custom designed RF and LO branch guide couplers and embedded commercial broadband IF MMIC LNA's from Avagotech, covering the 6-18 GHz band with a minimum noise factor (50 Ω system) of 1.8 dB.

State-of-the-art performance in terms of LO power consumption, mixer and receiver noise, image rejection and RF and LO VSWR is demonstrated showing good agreement with predicted performance. This is the first time that a high performance submillimeter wave 2SB Schottky receiver topology based on subharmonic mixers is demonstrated, setting new standards on future room temperature receiver systems and instruments.

II. ANALYSIS

A. Sideband Separating Topology

For fundamental mixers, sideband separating topology schemes are accomplished by feeding either the mixer LO or RF side with a 90 degree hybrid, see [24]. The upper sideband USB and lower sideband LSB can then be extracted by the use of a 90 degree IF hybrid. For sub harmonic x2 mixers however, the relative LO phase will effectively double in the down conversion process. Thus

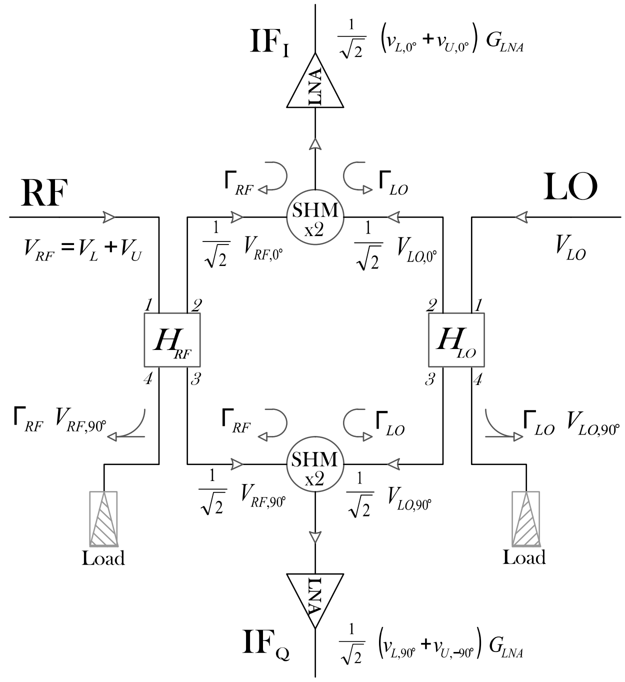

Fig. 2. Schematic of the 2SB receiver circuit topology employing sub harmonic mixers, hybrid couplers and IF LNA's, showing how the phase differences applied for the LO and RF signals lead to a balanced quadrature feeding configuration.

only half the phase difference is required for the LO feeding. This can simply be understood by looking at the trigonometric equation for the cosine square, which can be used as an idealized representation of the anti-parallel diode conductance waveform seen by the RF signal when pumped by a LO signal:

$$2\cos^2\left(\omega_{LO}t+\varphi_0\right)=1+\cos\left(2\omega_{LO}t+2\varphi_0\right) \tag{1}$$

The condition on the relative LO hybrid phase shift φ_0 for achieving effective LO quadrature phase in the down conversion process can be formulated as:

$$\varphi_0=45^\circ+n\cdot 90^\circ : n\in \mathrm{Z} \tag{2}$$

with n being an integer number. If we choose to go for RF quadrature conversion the conventional in-phase and out-of-phase LO hybrids used in fundamental mixer topologies are reduced to the following condition on the LO hybrid phase shift φ_0 :

$$\varphi_0=n\cdot 90^\circ : n\in \mathrm{Z} \tag{3}$$

with n being an integer number.

The main advantage of using the LO_{X2} quadrature topology (45-degree LO hybrid) is that an in phase or differential phase hybrid can be used for the RF. Due to symmetry properties of such hybrids the phase and amplitude balance is often close to ideal, in theory leading to a higher image rejection. Moreover, at submillimeter wavelengths, such hybrids can be easily realized in the form of a matched Y-junction [25], or a balanced E-plane probe [26]. This is the main motivation for implementing sideband separation by LO_{X2} quadrature feeding, especially for systems operating at a fixed or narrowband LO frequency.

However, the main drawback of the matched Y-junction and balanced E-plane probe is the poor output isolation as they lack an even-mode termination (corresponding to an odd-mode termination in a Wilkinson divider), which leads to large imbalance and ripple in the receiver response. Therefore such topologies have in principle been abandoned for most cryogenic fundamental 2SB receiver implementations. Another drawback of the 45 degree LO hybrid is the reduced LO input return loss as the reflected waves will recombine constructively in both the input and isolated port, leading to standing waves and larger imbalance. One solution would be to go for an integrated circuit topology using terahertz monolithic integrated circuits TMICs [27-29], for which the realization of planar in-phase hybrids with good output isolation, i.e. Wilkinson dividers is possible.

All together, when considering the realization of the 2SB receiver based on subharmonic mixers using conventional waveguide implementations for the hybrids, it is more advantageous to go for RF quadrature feeding by using a 90 degree hybrid, given that the bandwidth, phase, and amplitude imbalance requirements can be met. High performance waveguide 90 degree hybrids can be realized using multi-section branch guide couplers BGC's, with low loss and large frequency coverage. Such an implementation would provide the needed inter-mixer RF isolation and would also benefit from low RF input port VSWR, as the combined reflections from the two mixers would re-combine in the isolated port of the RF hybrid. It could also lead to better calibration accuracy of the radiometer system which is dependent on low RF VSWR.

Adopting the RF quadrature feeding leaves three options for the LO hybrid realization, see equation (3); either an in-phase or out-of-phase hybrid or a 90 degree hybrid can be used. Given the often poor LO match of mixers and output match of LO multipliers, the latter of the three options was chosen for realization. In Fig. 2 the proposed low VSWR topology is shown with the IF LNA's included in the IF IQ-paths. Using a similar convention as [5], the ideal process of subharmonic down conversion from the RF port to the IF I and Q ports can be described by expressing the downconverted IF voltages $v_{IF,I}$ and $v_{IF,Q}$ at the respective I and Q ports:

$$\begin{aligned} v_{IF,I} &= \frac{1}{\sqrt{2}}\left(v_{L,0^\circ} + v_{U,0^\circ}\right)\cdot G_{LNA} \\ v_{IF,Q} &= \frac{1}{\sqrt{2}}\left(v_{L,90^\circ} + v_{U,-90^\circ}\right)\cdot G_{LNA} \end{aligned} \tag{4}$$

with v_L and v_U being the downconverted V_L and V_U LSB and USB voltages respectively and G_{LNA} being the amplifier gain. By combining the I and Q signals in an IF quadrature network the USB signals and LSB signals become separated.

B. Noise

Another fundamental difference of the two discussed topologies can be found in their respective noise characteristics, assuming standard waveguide hybrids are used. The RF quadrature topology based on branch guide couplers requires a termination for the isolated hybrid port, which will radiate noise at its ambient temperature into the mixers, consequently increasing the receiver noise temperature. As this noise is entering through the isolated port of the hybrid, the IF ports of the down converted USB's and LSB's will be flipped compared to signals entering the hybrid input port. For the LO_{X2} quadrature topology implementation, which lacks an RF even mode termination, the noise generated at the mixer RF port will instead leak into the other mixer resulting in a increase of the total receiver noise. However due to poor mixer RF match, a ripple effect from RF standing waves is expected to be seen in the receiver characteristics.

If we assume an infinite sideband ratio SBR or image rejection IR, meaning that we have perfectly balanced mixers and ideal hybrids, the receiver noise for the proposed RF quadrature topology can simply be written as:

$$T_{rec,ssb} = T_{load} + T_{mix,ssb} + L_{mix,ssb} T_{LNA} \tag{5}$$

with $T_{mix,ssb}$ beeing the mixer SSB noise, T_{load} the effective load temperature, $L_{mix,ssb}$ the mixer SSB conversion loss and T_{LNA} the total input noise temperature from the LNA. The effect of image rejection becomes clear when measuring the Y-factor of a sideband separating receiver compared to a double sideband receiver. Since only half the hot and cold noise power is down converted to the respective IF port and due to the added noise coming from the hybrid load, the Y-factor is lowered considerably. In the ideal case, the measured Y-factor for the SSB receiver can be written as:

$$Y_{rec,ssb} = \frac{T_{hot} + T_{load} + T_{mix,ssb} + L_{mix,ssb}T_{LNA}}{T_{cold} + T_{load} + T_{mix,ssb} + L_{mix,ssb}T_{LNA}} \tag{6}$$

The intrinsic mixer noise of the 2SB receiver can now be calculated. The corresponding equation for the measured Y-factor of a DSB receiver can be written as:

$$Y_{rec,dsb} = \frac{2\cdot T_{hot} + T_{mix,ssb} + L_{mix,ssb}T_{LNA}}{2\cdot T_{cold} + T_{mix,ssb} + L_{mix,ssb}T_{LNA}} \tag{7}$$

and the mixer noise of the SSB receiver and DSB receiver can now be compared, either in the SSB domain or in the DSB domain. The DSB mixer noise is simply defined as:

$$T_{mix,dsb} = \frac{T_{mix,ssb}}{2} \quad (8)$$

The mixer DSB conversion loss is defined as:

$$L_{dsb} = \frac{L_{ssb}}{2} \quad (9)$$

A more in detail analysis of SSB and DSB receiver noise and system noise can be found in [30, 31].

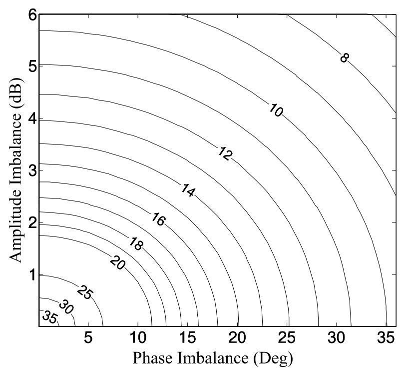

Fig. 3. Constant SBR contours as a function of phase and amplitude imbalance.

C. Image Rejection

The image rejection IR or sideband ratio SBR in a SSB mixer will be a function of the effective amplitude and phase imbalance in the system. The SBR can be defined as the ratio between the ideal additive and cancelling processes [6, 32]:

$$SBR = \sqrt{\frac{(1+\delta+\cos\alpha)^2 + \sin^2\alpha}{(1+\delta-\cos\alpha)^2 + \sin^2\alpha}} \quad (10)$$

with δ being the combined amplitude offset and α the combined phase error introduced by the system. By looking at the constant SBR contour plots, see Fig. 3, an upper limit on the phase and amplitude imbalance for a given SBR level can be determined. By measuring the SBR and IQ amplitude imbalance an upper limit of the phase imbalance can be determined. A more in detail analysis of the SBR response can be found in [33], in which a systematic approach, based on the symmetrical properties of the error functions of the individual components in the system is presented.

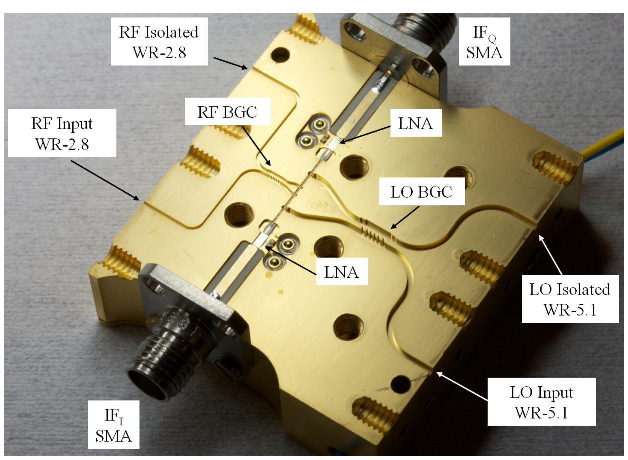

Fig. 4. Photo of the 2SB receiver module split block assembly, the module outer dimensions are roughly 40 by 40 mm.

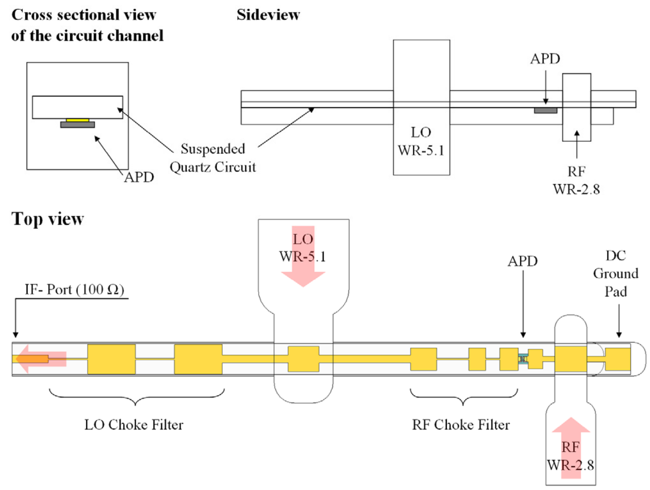

Fig. 5. DSB mixer design employing the suspended microstrip topology using a 70 µm quartz circuit with flip-chip soldered diode chip.

III. DESIGN

The low VSWR 2SB receiver topology was implemented as a waveguide integrated receiver module, see Fig. 4, specially designed for the possibility to characterize the intrinsic receiver parameters. It was also important to have the flexibility of running the system with various IF back-end configurations, why the receiver front-end was realized as an IQ-mixer receiver. The subharmonic IQ mixer SHIQ-Mixer prototype design had the following key features:

1) E-plane splitblock design with symmetrical layout of the RF, LO and IF ports.
2) Integrated IF LNA's for minimizing the effect of IF standing waves and for minimizing the effect of losses in the IF network on the total receiver noise.
3) Access to I and Q IF ports to be able to measure the intrinsic IQ-mixer phase and amplitude imbalance, apply IF tuning and for the possibility to use different IF-backend configurations.
4) Access to the input and isolated ports of the LO and RF hybrids, for the possibility of characterizing the full response.

The high flexibility of the prototype module comes to the cost of additional losses introduced by the long waveguide runs that had to be used in the RF and LO paths, approx. 0.5 dB and 0.2 dB respectively, slightly increasing the receiver noise and required LO power. No compensation for losses has been done in the presented data.

A. DSB Mixer Design

A suspended hybrid mixer topology design, using discrete anti-parallel diodes that are flip-chip soldered to a quartz carrier circuit was used. In Fig. 5 the layout schematic of the mixer is shown with the main features of the design. The mixer was designed for a diode structure with a total chip capacitance of around 10 fF and diode series resistance R_s of around 10 Ohm per anode. LO and RF matching is done both on circuit and in the rectangular waveguide to be able to simultaneously provide a broadband rejection in the choke filters.

B. Hybrids

The RF and LO hybrids were implemented as BGC's, machined directly in the split block housing. The RF hybrid parameters and layout are found in Fig. 6. It was designed to cover the 310-370 GHz band with nominal amplitude and phase imbalance better then 0.5 dB and 1 degree respectively and with an input return loss and isolation better than 20 dB. The LO hybrid design had a nominal amplitude and phase imbalance better then 0.4 dB and 0.5 degree respectively. The details of the LO coupler design can be found in [18]. For both designs the 3D-EM solver HFSS from Ansys Corp. was used. The simulated variation of the amplitude and phase imbalance assuming a 10 µm tolerance in dimensions, was found to be less then 0.3 dB and 0.5 degree for the LO hybrid, a tolerance in the assembly better then 5 µm was expected.

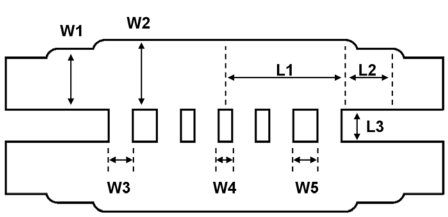

Fig. 6. RF WR-2.8 hybrid design with parameters in mm W1=0.394, W2=0.432, W3=0.155, W4=0.073, W5=0.130 L1=0.855, L2=0.279 and L3=0.173, the step transition radius was 0.150 mm.

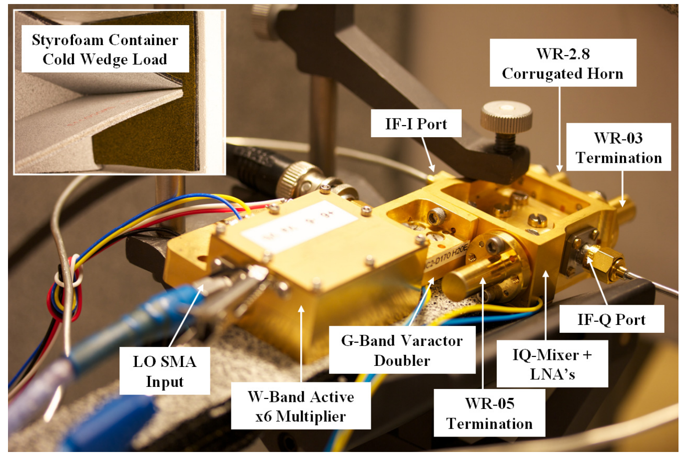

Fig. 7. Y-factor measurement setup showing the 2SB receiver with the horn pointing towards a cold Eccosorb™ wedge load inside a LN2 filled Styrofoam container (shown in the top left corner) that is place behind a tilted chopper wheel (not shown in the picture) covered in Eccosorb™ absorbing material working as a hot load. The IF IQ-cables are connected to a broadband 90-degree IF hybrid also not shown in the picture.

IV. Measurement Setup

For the evaluation of the receiver, three basic measurement setups were used, a Y-factor measurement setup shown in Fig. 7, a total power measurement setup for LO return loss characterization using a directional coupler and Erickson power meters (EPM2 and EPM4), and a continuous wave CW RF source setup used mainly for evaluation of the image rejection but also of the RF return loss to the isolated port.

The Y-factor measurement setup consisted of a tilted (for the reduction of RF standing waves), steerable chopper wheel, covered in Eccosorb™ working as the hot load, and a Eccosorb™ wedge load about 50 cm long, inside a LN2 filled Styrofoam container, working as the cold load. The Styrofoam material was transparent in the RF band and the compact arrangement made it possible to have the receiver WR-2.8 corrugated horn antenna from Radiometer Physics GmbH, could be positioned in close vicinity to the cold load without using any mirror.

The quadrature feeding of the designed SHIQ-Mixer enabled characterization of the combined internal DSB mixer LO and RF return loss passing through the hybrids. This was done by measuring the power at the hybrid isolated port, when applying a known power at the input port. The receiver RF input return loss was not measured as no directional coupler was available at the time of the experiment. For most of the measurements drift effects in both the CW-source and EPM had to be considered.

Two G-Band LO multiplier chains were assembled using Omnisys active W-band x6 multiplier modules and Chalmers broadband high power Schottky varactor doublers, together covering the 160 – 180 GHz band. As a last doubler stage to RF frequency a VDI Schottky doubler was used, which in the current setup could generate about 0.2 - 1 mW of output power covering most of the 320-360

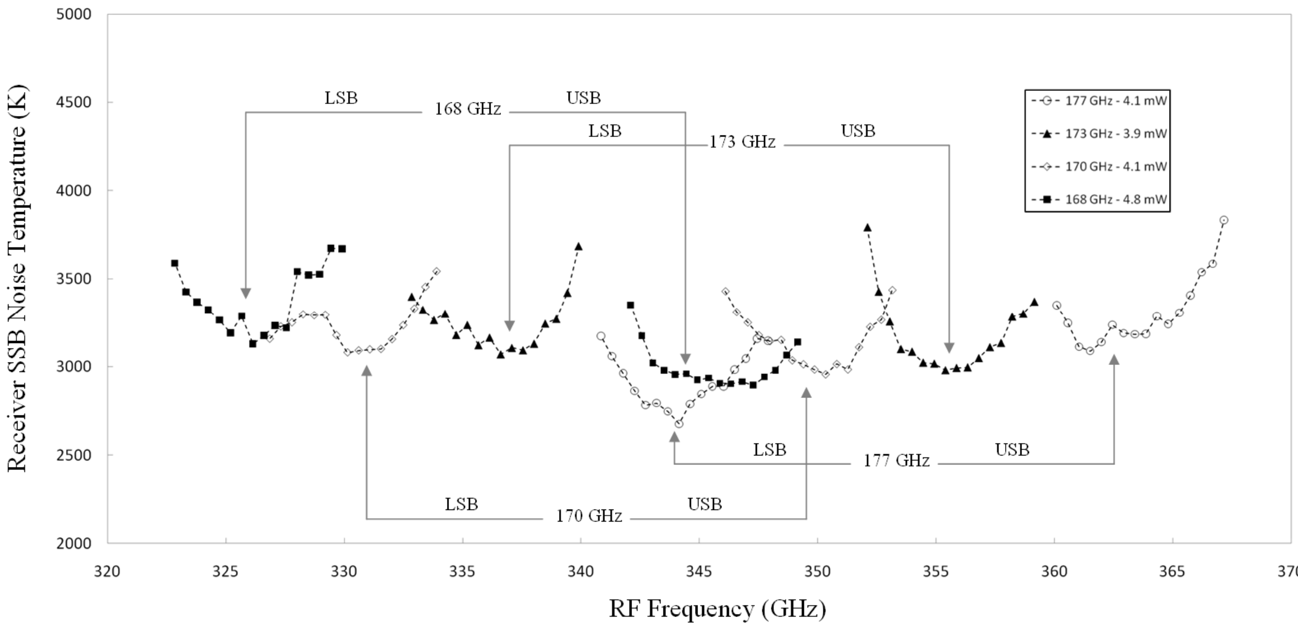

Fig. 8. Measured SSB receiver noise (assuming ideal SBR) in 6-13.2 GHz IF bands, including the extra 300 K noise from the RF load, at 168, 170, 173 and 177 GHz LO frequency and 4.8, 4.1, 3.9 and 4.1 mW LO power respectively.

GHz band. A fixed RF attenuator was also used not to saturate the receiver. Both the RF and LO source modules were controlled in a semi-automated setup using the Matlab instrument interface toolbox and look up tables enabling control of the output power.

Neither active temperature stabilization nor active power monitoring was done why calibration had to be done on daily basis together with calibration checks after each measurement series. On average the repeatability of the RF CW source during measurements was estimated to be better then 0.5 dB over most of the band.

V. RESULTS

A 2SB receiver module and two DSB receiver modules for comparison were assembled using VDI diodes with a specified maximum series resistance R_s of 13 Ω and total chip capacitance C_{tot} in between 7 fF and 11 fF. The diodes were supplied flip chip mounted on the mixer quartz circuits.

The DSB mixers had a minimum conversion loss and noise, including circuit and antenna losses, that were estimated through measurements to about 9 dB (SSB) and 800 K (DSB) respectively at a 4 GHz IF frequency. The typical 2SB receiver noise is about 3000 K (SSB) including the 300 K (SSB) contribution of the RF load termination, see Fig. 8. The SSB noise was calculated based on equation (6) assuming an infinite SBR. In reality the non ideal SBR has to be compensated for, see [34]. An image rejection of 15 dB would for instance lead to a 100 K overestimation of the receiver noise. By using equations (5)-(8) the effective mixer noise of the 2SB receiver was estimated to about 900 K (DSB), assuming a minimum LNA input noise of 150 K. Thus the 2SB receiver was operating close to optimum condition with comparable performance to the DSB receivers.

To be able to draw any conclusions on the repeatability of the mixer, a much larger amount of tested mixers and more detailed characterization would be required. Nevertheless, an attempt of estimating the tolerances and corresponding effect on phase and amplitude imbalance was made.

For the particular type of DSB mixer assembly, about 1 GHz of variation was observed in the measured LO return loss frequency response, corresponding to an effective variation of the diode total capacitance of about 1 fF. The larger part of this variation is thought to come from circuit misalignments.

Since the nominal LO coupler design had a 0.4 dB imbalance at the center frequency of 170 GHz, corresponding to a 10% difference in LO power reaching the two mixers, an imbalance in the mixers conversion loss would be expected, as well as in the LNA's, due to differences in the mixer's IF impedance. The dependency of the receiver conversion loss upon LO power was therefore tested. This was done by comparing the amplitude imbalance between the I and Q channels when connecting a CW source to the RF input. This measurement included the combined conversion gain of the mixer and LNA and response of the RF hybrid, and gave a good first indication on the operational condition of the receiver. For LO drive levels between 4-6 mW at 170 GHz, the maximum IQ amplitude imbalance was found to be about 2.5 dB with a 1 dB offset. A maximum change of about 0.5 dB between different LO power levels was also observed but with no clear trend.

TABLE I
BUDGET OF THE SYSTEM PHASE AND AMPLITUDE IMBALANCE

	QH_{RF}	QH_{LO}	LNA's	SHM's	QH_{IF} + Cables	Total
Δφ (Deg)	1	1	1.5	-	20	23.5
ΔA (dB)	0.5	-	0.25	1.75*	0.5	3

Phase imbalance Δφ in degrees, amplitude imbalance ΔA in dB for the RF hybrid QH_{RF}, LO hybrid QH_{LO}, LNA's, subharmonic mixers SHM's and IF hybrid QH_{IF} with cables, *estimate based on the measured IQ-amplitude imbalance.

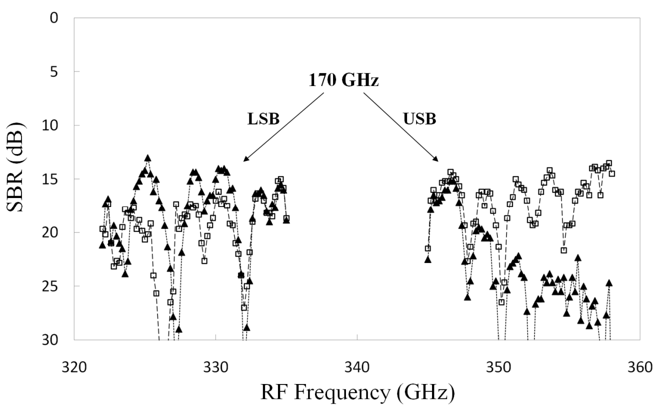

Fig. 9. Measured image rejection in a 5-18 GHz IF frequency range, at an LO drive of 6 mW at 170 GHz, for nominal IF system setup (▲) and for the case of flipping the IF system IQ-interconnects (□).

The imbalance of the LNA MMIC was also investigated. This was done by comparing two assembled modules with two cascaded embedded LNA MMIC's of the same type as those used in the 2SB receiver. A combined package phase and amplitude variation between the two modules of less than 3° and 0.5 dB respectively was measured. For the single amplifier chips embedded in the receiver the corresponding imbalance would be expected to be less then half given identical mixer IF impedances. The IF hybrid consisting of a broadband quadrature hybrid (QH-0226) from Marki Microwave and a pair of phase matched semi-rigid cables was also tested separately, showing an amplitude imbalance of less then 0.5 dB and a linearly increasing phase imbalance of up to 20° at 16 GHz IF frequency. The source of this phase error is thought to originate from the unequal bending of the semi rigid phase matched cables. All together the nominal total maximum phase and amplitude imbalance of the receiver was estimated to 3 dB and 23.5 degrees respectively. A phase and amplitude budget of the receiver system is presented in Table 1.

As the IF back-end's combined phase and amplitude imbalance could be expected to have a considerable effect on the image rejection response, especially at the upper part of the IF frequency band, all image rejection measurements were also made with flipped IF IQ connections, i.e. by shifting the IF hybrid ports including the phase matched cables, see Fig. 9 showing measurements at 170 GHz

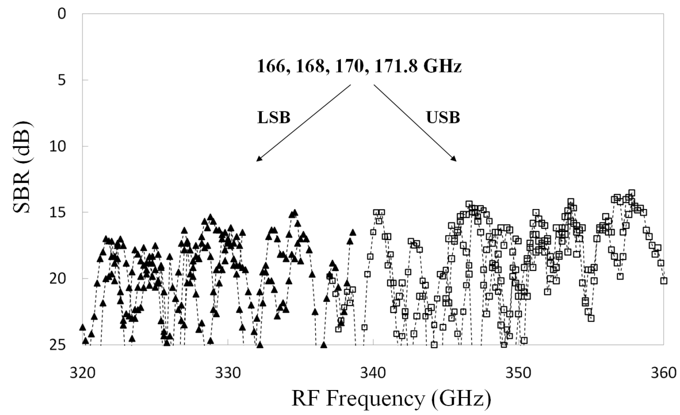

Fig. 10. Measured image rejection response for the LSB (▲) and USB (□) in 5-18 GHz IF frequency bands, at 166, 168, 170 and 171.8 GHz LO frequency and 6.3, 4.8, 6.1 and 3.9 mW LO power respectively.

LO frequency. The result shows a clear improvement of the SBR in the upper part of the USB and clear degradation of the SBR in the lower part of the LSB when shifting the IF hybrid, pointing to an asymmetrical IQ phase imbalance as would be expected. The typical minimum image rejection was found to be around 15 dB, see Fig 10, indicating on a system maximum amplitude and phase imbalance of around 3 dB and 15 degrees respectively, consistent with the system imbalance budget.

On average the minimum IR improved by 2 dB, when increasing the LO power from 4 mW to 6 mW. The repeatability of the measured image rejection was tested and on average variations of less then 0.5 dB could be seen at image rejection levels of around 15 dB. This result was also consistent with the estimated repeatability of the RF CW source.

The repeatability of the hybrid mixer assembly was examined by means of simulations. In particular the effect of circuit misalignment was investigated, which could effectively be as large as 10 µm. The largest effect was seen in the case of a circuit misalignment sideways, meaning a circuit shift along the propagation of the LO and RF waveguides, with a frequency shift of the LO input return loss characteristic of around 2 GHz, corresponding to about 2 fF of effective change in the diode's total capacitance.

By combining 3D-EM simulations of the DSB mixer and LO and RF hybrids, the 2SB mixer characteristics could be modeled, see Fig. 11. The degradation of the image rejection for the case of a circuit misalignment of 10 µm sideways is quite severe, reducing the image rejection to a 10 dB level. Given the measured image rejection level of the 2SB receiver, the effective misalignment of the circuits must have been much smaller than 10 µm, this was also confirmed by visual inspection. By adding the RF hybrid the image rejection is limited to levels below 25 dB. The bandwidth of the RF hybrid design was about 70 GHz. A re-design of the coupler for the 320-340 GHz band could potentially improve the nominal 0.5 dB amplitude imbalance to about 0.25 dB.

Simulations also showed that the image rejection was largely improved when increasing the LO power. The large amplitude imbalance of the hybrid, sharp turn-on characteristic of the mixer, saturation effects and mixer LO mismatch, are believed to be the main reasons for this behavior. Consequently the image rejection could largely benefit by a slight increase of the LO power drive. And the dependency of mixer conversion loss as well as mixer IF impedance upon LO power has to be considered. A clear advantage of operating the LO at frequencies close to the optimum return loss point compared to operation at the band edge, were also observed in simulations.

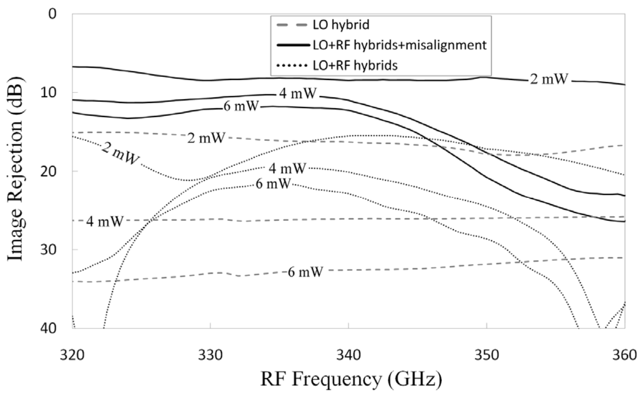

Fig. 11. Simulated image rejection at different LO powers, including only the LO hybrid (--), then adding the RF hybrid (··) and finally introducing a circuit misalignment of 10 µm in one of the mixers (solid).

In [35], a conversion loss variation of a similar DSB mixer is estimated to about 0.5 dB over an optimum LO power range of 2 to 3 mW for which a low receiver noise is maintained. This would mean that the expected difference in the conversion loss between two identical mixers, using a LO hybrid with 0.2 dB imbalance would be less then 0.05 dB at a nominal LO drive corresponding to 1.5 mW per mixer. For fixed LO frequency operation the LO hybrid could in principle be designed for perfect amplitude balance.

The receiver LO input return loss was measured from 161 GHz to 177 GHz in 0.2 GHz steps and was found to be better then 15 dB over most of the measured band. Measured and simulated data (assuming identical mixers) at different LO drives, is presented in Fig. 12 showing the advantage of using the 90 degree hybrid topology.

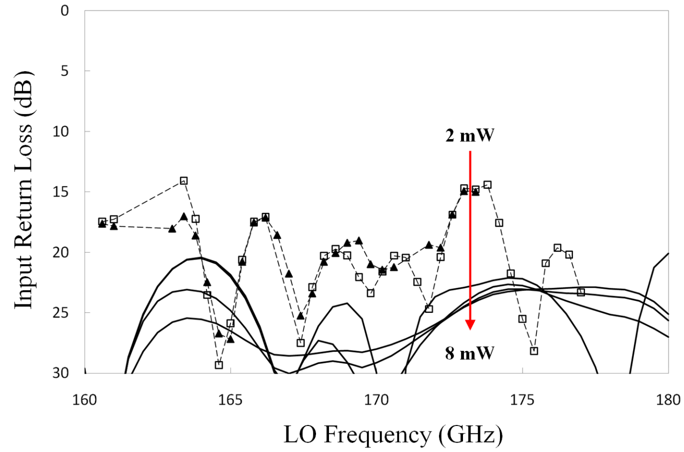

Fig. 12. Measured (discrete) and simulated (solid) receiver LO input return loss. Measured at 2 mW (□) and 4 mW(▲) of LO power and simulated for 2, 4, 6 and 8 mW of LO power assuming 1 dB of insertion loss.

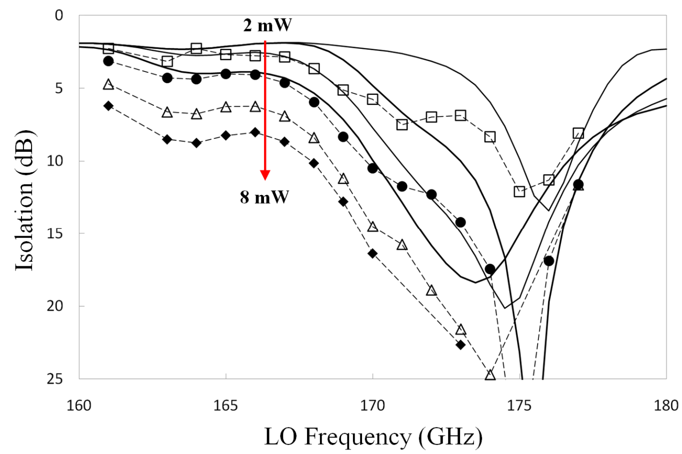

Fig. 13. Measured (discrete) and simulated (solid) receiver LO port isolation at an LO pump frequency of 170 GHz and 2, 4 6 and 8 mW of LO power applied, assuming 1 dB of LO insertion loss in the simulations.

The measured transmission from the LO input port to the isolated port is presented in Fig. 13 and compared with simulations. The isolation curves are the combined response of the intrinsic DSB mixer's LO return loss and response of the LO hybrid, corresponding to the return loss of a DSB mixer.

Measured results on the corresponding transmission from the RF input port to the isolated port, are presented in Fig. 14, showing good agreement with simulations. For comparison the simulated RF input return loss is also plotted showing the advantage of quadrature feeding.

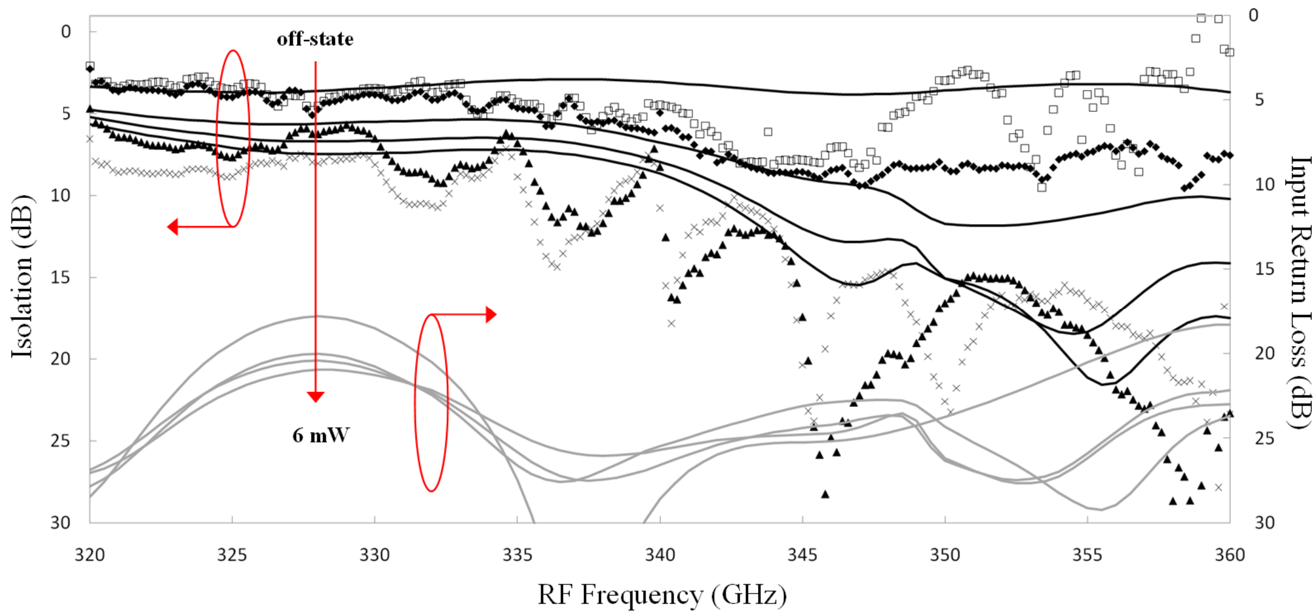

Fig. 14. Simulated (solid) and measured (discrete) receiver RF port isolation and simulated receiver input return loss (solid grey), at an LO pump frequency of 170 GHz, for off-state and for 2, 4 and 6 mW of LO power applied, assuming a LO and RF insertion loss of 1 dB and 1.5 dB respectively in the simulations.

VI. Conclusion

A novel broadband sideband separating topology, with low VSWR characteristics, employing sub-harmonic Schottky diode mixers and LO and RF 90-degree hybrids has been demonstrated as an integrated 2SB receiver module operating in the 320 - 360 GHz band. As the main results a nominal SBR of 15 dB untuned and a receiver noise consistent with the performance of state-of-the-art DSB receivers is measured, over most of the band.

From a tolerance analysis perspective, the effect of misalignment in the mixer circuits is found to be the main limiting factor for reaching higher SBR levels. By optimum design of the hybrids and by using TMIC technology the SBR could be improved to some degree, however to reach really high SBR levels compensation of the IQ-imbalance is needed. This can be done either in the analog domain using standard microwave components, or in the digital domain using complex IQ auto-correlators in combination with advanced digital correction algorithms. In theory IQ-tuning could reduce all the fixed phase and amplitude errors in the system, but would in practice depend on the accuracy of the implemented compensation scheme and stability of the system.

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References

[1] A. Wootten, A.R. Thompson, "The Atacama Large Millimeter/Submillimeter Array," *Proceedings of the IEEE* , vol.97, no.8, pp.1463-1471, Aug. 2009.

[2] P. Siegel, "THz Instruments for Space," *IEEE Transactions on Antennas and Propagation*, vol.55, no.11, pp.2957-2965, Nov. 2007.

[3] ESA SP-1313/5 Candidate Earth Explorer Core Missions – Reports for Assessment: PREMIER – Process Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation, 2008, ISBN 978-92-9221-406-7, ISSN 0379-6566M.

[4] D. Meledin, A. Pavolotsky, V. Desmaris, I. Lapkin, C. Risacher, V. Perez, D. Henke, O. Nystrom, E. Sundin, D. Dochev, M. Pantaleev, M. Fredrixon, M. Strandberg, B. Voronov, G. Goltsman, V. Belitsky, "A 1.3-THz Balanced Waveguide HEB Mixer for the APEX Telescope," *IEEE Transactions on Microwave Theory and Techniques*, vol.57, no.1, pp.89-98, Jan. 2009.

[5] F.P. Mena, J.W. Kooi, A.M. Baryshev, C.F.J. Lodewijk, T. Zijlstra, R. Hesper, G. Gerlofsma, T.M. Klapwijk, W. Wild , "Design and Performance of a 600–720-GHz Sideband-Separating Receiver Using AlO_x and AlN SIS Junctions," *Microwave Theory and Techniques, IEEE Transactions on* , vol.59, no.1, pp.166-177, Jan. 2011.

[6] S. Claude, C. Cunningham, A. Kerr and S.-K. Pan, "Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids", *ALMA Memo 316*. Sept., 2000.

[7] I. Mehdi, S. Marazita, D. Humphrey, L. Trong-Huang, R. Dengler, J. Oswald, A. Pease, S. Martin, W. Bishop, T. Crowe, P. Siegel, "Improved 240-GHz subharmonically pumped planar Schottky diode mixers for space-borne applications," *IEEE Transactions on Microwave Theory and Techniques*, vol.46, no.12, pp.2036-2042, Dec 1998.

[8] J. Hesler, W. Hall, T. Crowe, R. Weikle, II, B. Deaver, Jr., R. Bradley, and S. K. Pan, "Fixed-tuned submillimeter wavelength waveguide mixers using planar Schottky barrier diodes," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 5, pp. 653–658, May 1997.

[9] T. Crowe, D. Porterfield, J. Hesler, W. Bishop, D. Kurtz and K. Hui, "Terahertz sources and detectors", *Proc. SPIE 5790*, 271, 2005.

[10] A. Maestrini, B. Thomas, H. Wang C. Jung, J. Treuttel, Y. Jin, G. Chattopadhyay, I. Mehdi and G. Beaudin, “Schottky diode-based terahertz frequency multipliers and mixers,” *Comptes Rendus de l’Academie des Sciences, Physique*, vol.11, no.7-8, pp.480-495, 2010.

[11] H.-W. Hubers, "Terahertz Heterodyne Receivers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol.14, no.2, pp.378-391, March-april 2008.

[12] T. Oxley, “50 years development of the microwave mixer for heterodyne reception,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, p. 867-876, Mar. 2002.

[13] Cohn, J Degenford, B. Newman, "Harmonic Mixing with an Anti-Parallel Diode Pair," *1974 S-MTT International Microwave Symposium Digest*, vol.74, no.1, pp. 171- 172, June 1974.

[14] M. Shimozawa, K. Kawakami, K. Itoh, A. Iida, O. Ishida, "A novel, sub-harmonic pumping direct conversion receiver with high instantaneous dynamic range," *IEEE MTT-S International Microwave Symposium Digest, 1996.,* , vol.2, no., pp.819-822 vol.2, 17-21 June 1996.

[15] I.-H. Lin, K.M.K.H. Leong, C. Caloz, T. Itoh, "Dual-band sub-harmonic quadrature mixer using composite right/left-handed transmission lines," *IEE Proceedings - Microwaves, Antennas and Propagation* , vol.153, no.4, pp. 365- 375, August 2006.

[16] H.-K. Chiou, W.-R. Lian, T.-Y. Yang, "A Miniature Q-Band Balanced Sub-Harmonically Pumped Image Rejection Mixer," *Microwave and Wireless Components Letters, IEEE* , vol.17, no.6, pp.463-465, June 2007.

[17] J. W. Archer and J. Tello, “A 180–196 GHz image-reject Schottky-diode MMIC mixer,” *Microw. Opt. Technol. Lett.*, vol. 49, no. 10, pp. 2319–2322, Oct. 2007.

[18] P. Sobis, J. Stake and A. Emrich, “A 170 GHz 45 degree Hybrid for Submillimeter Wave Sideband Separating Subharmonic Mixers” *IEEE Microwave and Wireless Components Letters*, vol. 18, NO. 10, pp. 680-682, Oct. 2008.

[19] P. Sobis, A. Emrich and J. Stake, "STEAMR Receiver Chain" *20th International Symposium on Space Terahertz Technology, ISSTT 2009,* Charlottesville, VA, USA, pp.320-325, Apr. 2009.

[20] P. Sobis, A. Olsen, J. Vucusic, V. Drakinskiy, S. Cherednichenko, A. Emrich and J. Stake, "Compact 340 GHz Receiver Front-Ends," *20th International Symposium on Space Terahertz Technology, ISSTT 2009,* Charlottesville, VA, USA, pp.183-189, Apr. 2009.

[21] B. Thomas, S. Rea, B. Moyna, B. Alderman, D. Matheson, "A 320–360 GHz Subharmonically Pumped Image Rejection Mixer Using Planar Schottky Diodes," *IEEE Microwave and Wireless Components Letters,* vol.19, no.2, pp.101-103, Feb. 2009.

[22] P. Sobis, J. Stake, A. Emrich, "High/low-impedance transmission-line and coupledline filter networks for differential phase shifters," *IET Microwaves, Antennas & Propagation,* vol.5, no.4, pp.386-392, March 21 2011.

[23] W. Bishop, K. McKinney, R. Mattauch, T. Crowe, G. Green, "A Novel Whiskerless Schottky Diode for Millimeter and Submillimeter Wave Application," *1987 IEEE MTT-S International Microwave Symposium Digest,* vol.2, no., pp.607-610, May 9 1975-June 11 1987.

[24] S. Maas, “Microwave Mixers”, 2nd edition, Artech House, 1993, ISBN 0-89006-605-1.

[25] A. Kerr and N. Horner, “A broadband in-phase Waveguide Power Divider/Combiner”, *ALMA Memo 325*. Oct., 2000.

[26] V. Vassilev, V. Belitsky, D. Urbain, S. Kovtonyuk , "A new 3-dB power divider for millimeter-wavelengths," *IEEE Microwave and Wireless Components Letters,* vol.11, no.1, pp.30-32, Jan. 2001.

[27] E. Schlecht, J. Gill, R. Dengler, R. Lin, R. Tsang, I. Mehdi, "A Unique 520–590 GHz Biased Subharmonically-Pumped Schottky Mixer," *IEEE, Microwave and Wireless Components Letters,* vol.17, no.12, pp.879-881, Dec. 2007.

[28] E.T. Schlecht, J.J. Gill, R.H. Lin, R.J. Dengler, I. Mehdi, "A 520–590 GHz Crossbar Balanced Fundamental Schottky Mixer," *IEEE, Microwave and Wireless Components Letters,* vol.20, no.7, pp.387-389, July 2010.

[29] H. Zhao, A.-Y. Tang, P. Sobis, T. Bryllert, K. Yhland, J. Stenarson, J. Stake, "Submillimeter Wave S-Parameter Characterization of Integrated Membrane Circuits," *IEEE, Microwave and Wireless Components Letters,* vol.21, no.2, pp.110-112, Feb. 2011

[30] H.T., Friis, “Noise Figures of Radio Receivers,” *Proc. Of the IRE,* July, 1944, pp 419-422.

[31] A. Kerr and J. Randa, “Thermal Noise and Noise Measurements-A 2010 Update,” *IEEE Microwave Magazine*, vol. 11, no. 6, p. 40-52.

[32] A. Emrich, “Spectrometers and Receiver Systems for Ground, Balloon and Satellite Based (Sub)millimeter Radio Astronomy,” *Ph. D dissertation*, *School of Engineering and Technology*, Chalmers university of Technology, Technical Report No. 225, 1992.

[33] A. Tasic, W.A. Serdijn, "Concept of spectrum-signal transformation," *IEEE International Symposium on Circuits and Systems, 2002. ISCAS 2002.*, vol.5, no., pp. V-449- V-452 vol.5, 2002.

[34] A. Kerr, S.-K. Pan and J. Effland, “Sideband Calibration of Millimeter-Wave Receivers”, *ALMA Memo 357*. Mar., 2001.

[35] B. Thomas, A. Maestrini and G. Beudin, “A low-noise fixed-tuned 300-360-GHz sub-harmonic mixer using planar Schottky diodes,” *Microwave and Wireless Components Letters*, IEEE, vol. 15, No. 12, pp. 865-867, Dec. 2005.

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