DESIGN OF PLANAR IMAGE SEPARATING AND BALANCED SIS MIXERS

A. R. Kerr and S.-K. Pan

National Radio Astronomy Observatory*
Charlottesville, VA 22903

Abstract

With noise temperatures of SIS receivers now in the range 2-4 times the photon temperature (hf/k), the overall sensitivity of radio astronomy measurements can be seriously degraded by atmospheric noise, and sometimes by noise from the local oscillator source. In spectral line measurements, atmospheric noise in the unwanted (image) sideband can be eliminated by using an image separating scheme. To reduce local oscillator noise, balanced mixers can be used.

It is possible to realize image separating and balanced mixers using quasioptical or waveguide RF circuits, but they are difficult to fabricate and bulky. We believe it is now practical to include the necessary signal and LO power dividers, couplers, and cold loads with the SIS mixer on the same quartz substrate. The complete image separating or balanced mixer can be fabricated using a standard niobium SIS mixer fabrication process with one or two additional layers.

We describe the design of single-chip balanced and image separating mixers for 200-300 GHz. The circuits are designed using a modified form of coplanar transmission line which has a convenient range of characteristic impedances while minimizing coupling to adjacent circuit elements. It is hoped ultimately to combine the image separating and balanced designs to make a balanced image separating mixer on a single chip.

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The Virtues of Image Separating Mixers

While most mixer receivers respond to both upper and lower sidebands, the majority of applications require only a single sideband response. Signals and noise received in the unwanted (image) sideband degrade the overall system sensitivity. At the NRAO 12-m telescope at Kitt Peak in Arizona, the antenna temperature at the zenith is typically 60 K at 230 GHz. In spectral line measurements with a double-sideband SIS receiver, the image noise contributes ~30% of the overall system noise, thereby doubling the integration time required to attain a given sensitivity.

There are three ways to eliminate the image response of a broadband mixer receiver: (i) A filter can be inserted in front of the mixer, which terminates the mixer reactively at the image frequency. This is difficult in widely tunable receivers. (ii) A tunable four-port diplexer with a cold image termination can be used. This can be done quasioptically, *e.g.*, using a Martin-Puplett interferometer as a sideband diplexer, but has a limited IF fractional bandwith and is cumbersome at millimeter wavelengths. (iii) A phasing type of image separation mixer can be used, as will be discussed below.

Types of Image Separating Mixer

At microwave frequencies, the usual realization of an image separating mixer, shown in Fig. 1, uses a quadrature hybrid to couple the LO to two identical (balanced) mixers with a π/2 phase difference. The signal power is divided equally between the mixers with zero phase difference, and the IF outputs of the two mixers are connected to an IF quadrature hybrid. The down-converted upper and lower sideband signals appear seperately at the two output ports of the IF hybrid. The in-phase and π/2 couplers in the signal and LO paths can be interchanged without losing image separation.

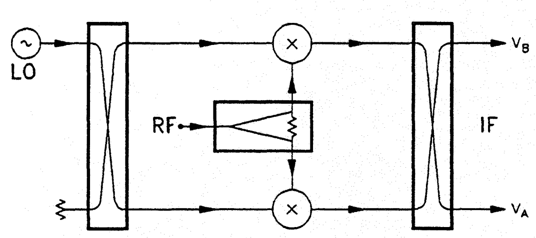

Fig. 1. A common configuration for an image separating mixer, consisting of LO and IF quadrature hybrids, and an RF in-phase power splitter.

A 100 GHz image separating mixer, using a waveguide magic-T and an adjustable phase shifter in the LO path to one mixer, has been described in [1], see Fig. 2. At shorter wavelengths, the signal and LO phasing can be done quasi-optically, as described in [1] and [2]. A quasi-optical image separating scheme is shown in Fig. 3, in which a crossed-grid power splitter [3] acts as an in-phase beam-splitter for the input signal, and splits the circularly polarized LO beam into two linearly polarized beams with π/2 phase difference. Inclined-grid couplers couple typically 1% of the LO power into each mixer, with 99% of the signal. Even at 250 GHz, such a quasi-optical scheme is physically cumbersome, and requires a large cryostat if several receivers are to be attached to the same refrigerator.

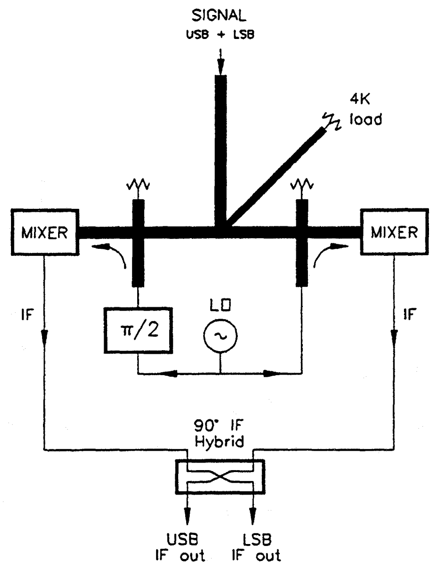

Fig. 2. The 100 GHz image separating mixer of [1] based on a waveguide magic–T.

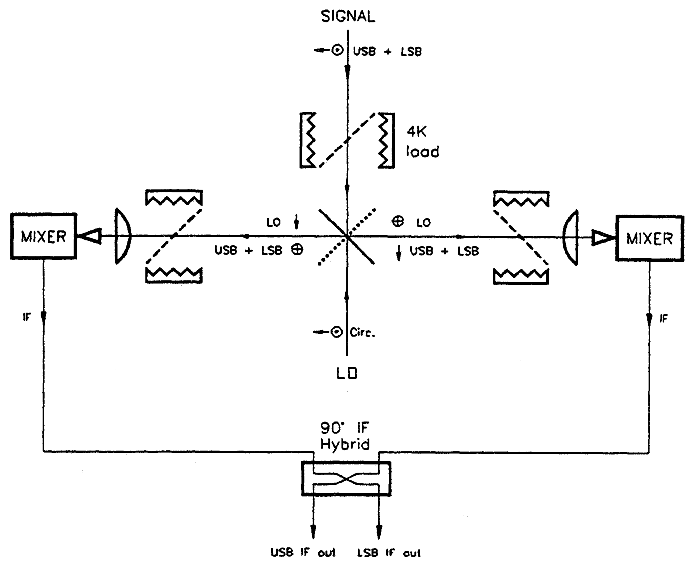

Fig.3 A possible quasi-optical image separating mixer using a 45° signal polarization selector, a crossed-grid signal and LO splitter, and inclined-grid LO couplers.

It is important to note that, in all image separating mixers, noise from the termination on the fourth port of the signal input coupler is down-converted and appears at the IF output ports.

In the present work, a scheme similar to that of Fig. 1 is used, but with the signal and LO ports interchanged, so the signal enters through a quadrature hybrid, and the LO through an in-phase power splitter. The RF quadrature hybrid, LO power divider, LO couplers, and SIS mixers are all fabricated on the same quartz substrate.

Choice of Transmission Line Medium

To avoid the need for very thin quartz substrates, the circuit is designed with thin-film ground plane, dielectric layer, and wiring-layer conductors all on the same side of a thick quartz substrate. The dimensions of coplanar transmission lines are kept substantially smaller than the substrate thickness to prevent the fields penetrating appreciably through the substrate.

The extermal RF source and IF load impedances are near 50 ohms. The characteristic impedances required in the RF quadrature hybrid and the matching circuit of the SIS mixer range from 3 to 116 ohms. The lower values are readily obtained with superconducting microstrip lines, while coplanar waveguide (CPW) can be used for the higher impedances. In the range from about 10 to 60 ohms, microstrip lines with thin-film dielectrics are too narrow to use, while CPW requires very narrow gaps between center conductor and ground plane. We therefore lower the characteristic impedance of CPW by using periodic capacitive loading.

A capacitively loaded coplanar waveguide (CLCPW) can be regarded as a standard CPW with periodic capacitors to ground. The equivalent circuit of a section of CLCPW is shown in Fig. 4; with 570 nm SiO, the characteristic impedance of this CLCPW is 63 ohms. For the CLCPW's used in this work, simulation using Sonnet *em* [4] indicates that the inductors L_1 and L_2 can be ignored if the reference plane is chosen at the center of the bridge, as shown.

Additional important advantages of CLCPW over standard CPW are that the periodic capacitors act as ground bridges, and: (i) greatly reduce coupling between adjacent components, and (ii), prevent odd-mode gap resonances in long CPW lines.

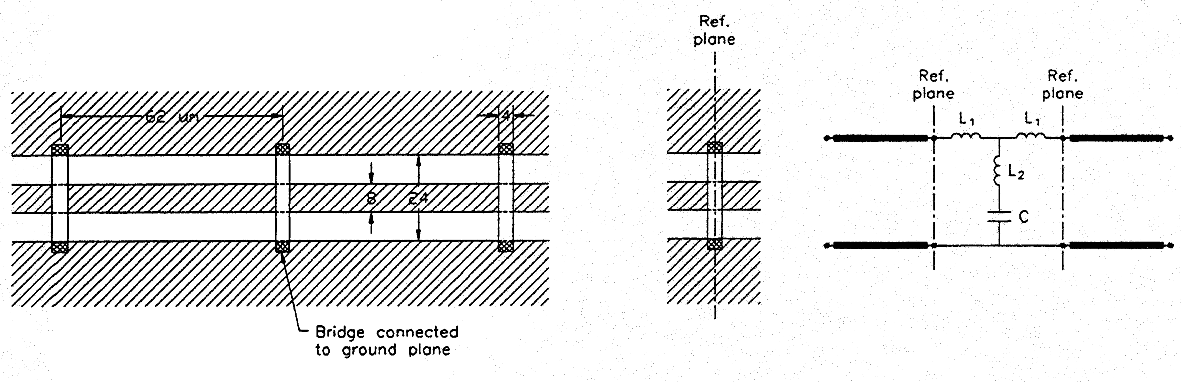

Fig. 4. A length of capacitively loaded coplanar waveguide (CLCPW), and equivalent circuit. Dimensions are in microns.

An Integrated Image Separating SIS Mixer for 200-300 GHz

The mixer is on a 2 x 1 mm quartz substrate, mounted in a block with separate waveguide inputs for the signal and LO, as shown in Fig. 5. Coupling from the waveguide to the mixer substrate is by broadband probes and suspended-stripline on smaller quartz substrates. Connections between the probes and the main substrate are by thin Au ribbon. IF and bias connections are by short wire bonds.

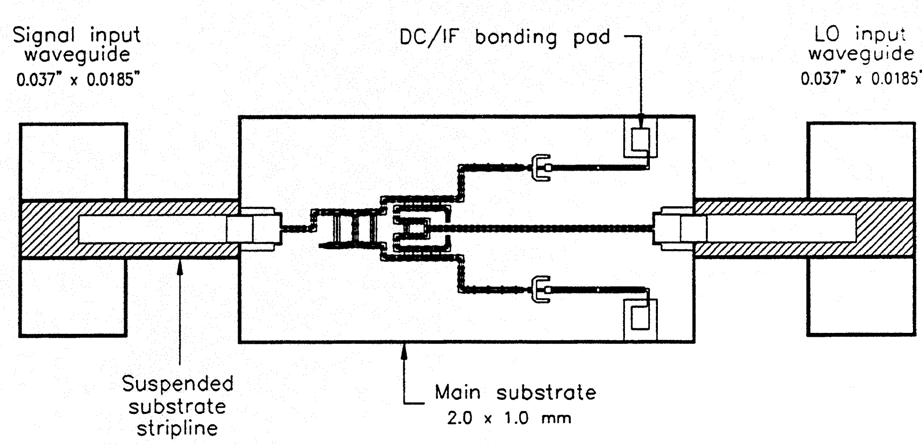

Fig. 5. The image separating mixer, showing the signal and LO waveguides, suspended stripline coupling probes, and the main substrate.

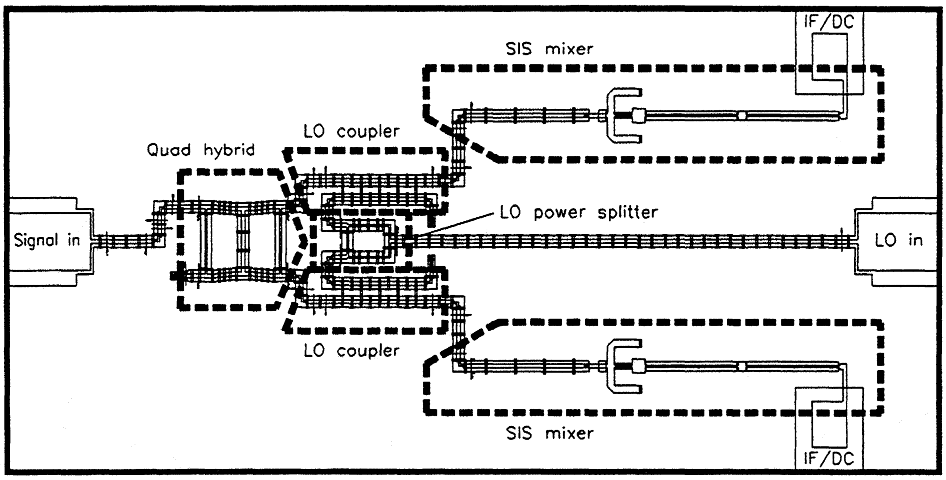

Fig. 6. Main substrate of the image separating mixer, showing the main components.

An enlarged view of the substrate is shown in Fig. 6. The main components are: (i) a 3 dB quadrature hybrid at the signal input, (ii) a 17 dB LO injection coupler in front of each mixer, (iii) an in-phase power splitter in the LO path, and (iv) two SIS mixers. Noise from the resistive termination on the fourth port of the input hybrid is downconverted to appear at the IF output ports of the mixer.

Amplitude & Phase Requirements

The image rejection obtainable in the image separating mixer depends on the amplitude and phase balance of the two quadrature hybrids and the mixers. The signal flow through the circuit is depicted in Fig. 7. The quantities c_1, c_2, and t_1, t_2, are the coupled port and through port scattering parameters (s_{21} and s_{31}) of the input hybrid (c_1, t_1) and IF output hybrid (c_2, t_2). Using the notation in the figure, the amplitudes at IF ports A and B are:

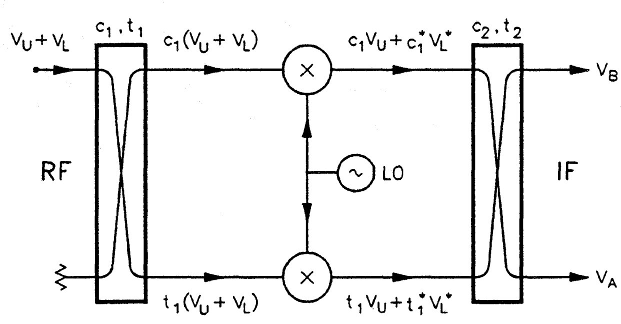

Fig. 7. Signal flow through the image separating mixer. For simplicity, the mixers are assumed to have unit conversion gain. V_U and V_L are the complex amplitudes of the incident USB and LSB signals.

$$V_A = V_U t_1 t_2 \left[\frac{c_2}{t_2} + \frac{c_1}{t_1}\right] + V_L t_1^* t_2 \left[\frac{c_2}{t_2} + \frac{c_1^*}{t_1^*}\right],$$

and
$$V_B = V_U t_1 t_2 \left[1 + \frac{c_1}{t_1}\frac{c_2}{t_2}\right] + V_L t_1^* t_2 \left[1 + \frac{c_1^*}{t_1^*}\frac{c_2}{t_2}\right].$$

At IF port A, the sideband amplitude ratio(LSB/USB) is $\dfrac{\dfrac{c_2}{t_2} + \dfrac{c_1^*}{t_1^*}}{\dfrac{c_2}{t_2} + \dfrac{c_1}{t_1}}$, and

at IF port B, the sideband amplitude ratio(USB/LSB) is $\dfrac{1 + \dfrac{c_1}{t_1}\dfrac{c_2}{t_2}}{1 + \dfrac{c_1^*}{t_1^*}\dfrac{c_2}{t_2}}$. It is clear that the image rejection depends on the deviation of $|c/t|$ from unity, and the deviation of $\arg(c/t)$ from $-\pi/2$, in the two hybrids. (If the mixers have unequal conversion loss, the difference can be included in c_1 and t_1.)

In the ideal case, $t_1 = t_2 = \frac{1}{\sqrt{2}}$, and $c_1 = c_2 = \frac{1}{\sqrt{2}} e^{-j\frac{\pi}{2}}$, and perfect image rejection results, with $V_A = V_U e^{-j\frac{\pi}{2}}$ and $V_B = V_L$. With non-ideal hybrids, the worst-case image rejection is plotted in Fig. 8 as a function of amplitude imbalance and phase imbalance. The amplitude and phase imbalance are the combined quantities (sum of magnitudes) for the two couplers and mixers. From the figure it is clear that to ensure 20 dB image rejection, the amplitude imbalance (for the whole circuit) must be < 1.7 dB <u>or</u> the phase imbalance < 12°. For 10 dB image rejection, the amplitude imbalance must be < 5.7 dB <u>or</u> the phase imbalance < 35°. The surprisingly large allowable asymmetry is a result of dealing with sums and differences of complex amplitudes, rather than powers.

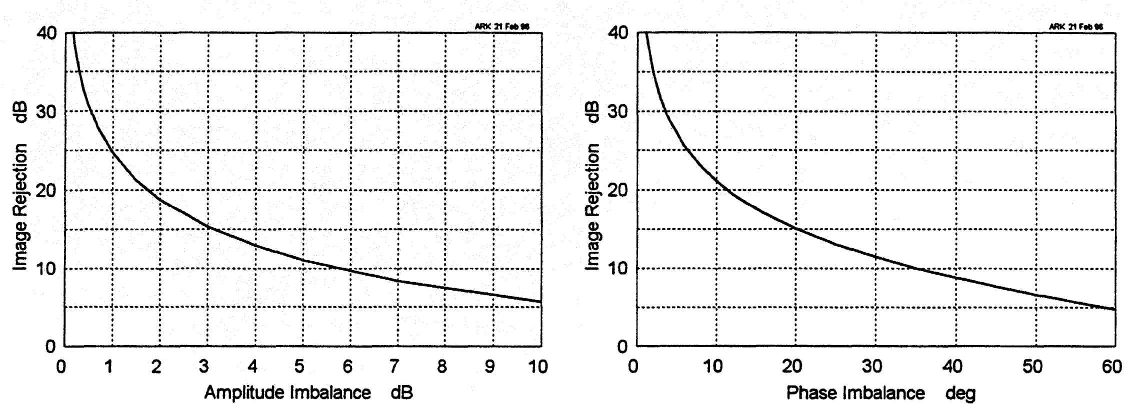

Fig. 8. Image rejection as functions of amplitude and phase imbalance for an image separating mixer.

Description of the Components

Input Quadrature Hybrid

Branchline directional couplers have been used for many years in stripline, microstrip, and waveguide circuits, and their design is well documented [5]. Within the design frequency band, the amplitude and phase variation decrease as the number of branches in the coupler increases, but the branch characteristic impedances increase. To keep the characteristic impedances in a suitable range, a three branch design was used, which for a 50-ohm nominal impedance requires sections with impedances 39, 47, and 116 ohms. For the frequency range 200-300 GHz, it is theoretically possible to obtain amplitude tracking within 1.2 dB, and phase tracking within 1.2° from 90°.

To realize a branchline coupler in CLCPW, Sonnet *em* was used to characterize the individual components (CPW sections, CLCPW bridges, and T-junctions), then MMICAD [6] was used to optimize the design. Finally *em* was used to analyse the whole coupler. The hybrid is shown in Fig. 9. A 1000 x scale model was built and measured with a vector network analyser. Fig. 10 shows the predicted performance of the optimized MMICAD design. Fig. 11 shows the results of the *em* analysis of the complete hybrid, and Fig. 12 shows the results measured on the 1000 x scale model.

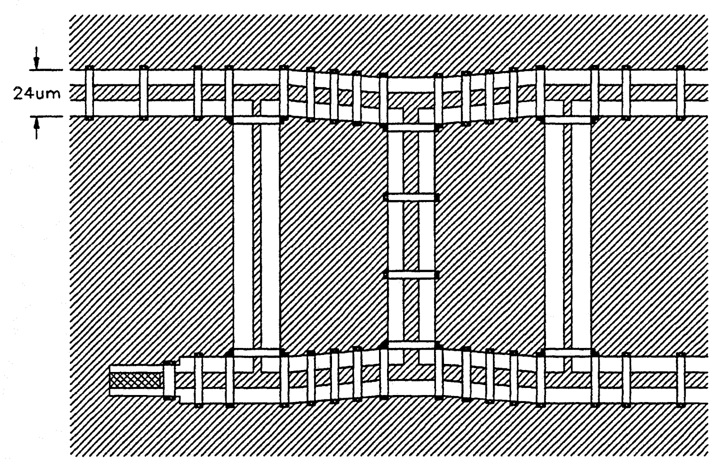

Fig. 9. Quadrature hybrid, including a matched termination in the lower left corner.

The obvious differences between the MMICAD and Sonnet *em* simulations are attributed to coupling beyond adjacent components of the circuit. Very close agreement is seen between the Sonnet *em* simulations and the results measured on the scale model.

LO Couplers

The LO couplers use two parallel CLCPW's with periodic capacitive coupling strips between the lines, as shown in Fig. 13. Again, equivalent circuits for individual sections of the coupler were deduced using Sonnet *em* and MMICAD. The design was optimized using MMICAD, and the final design checked using *em*. Fig. 14 shows the *em* results for the the final design. The coupling varies from 19-15 dB over the 200-300 GHz band, while the input return loss ≥ 28 dB and the directivity > 9 dB.

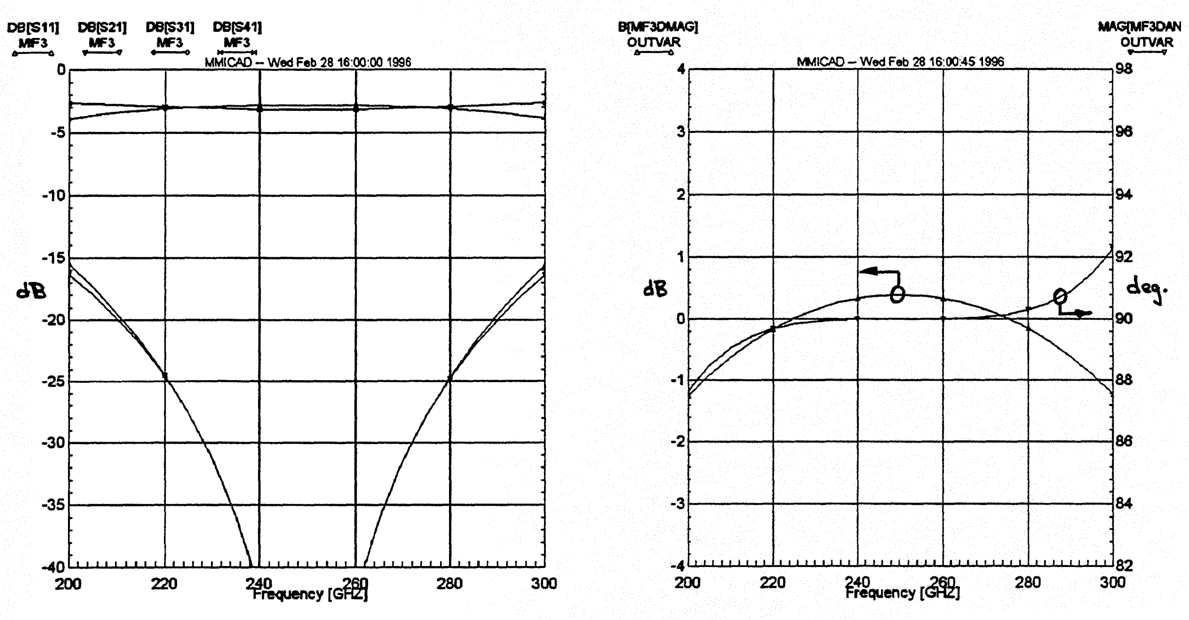

Fig. 10. S-parameters of the quadrature hybrid after optimization of the circuit model.

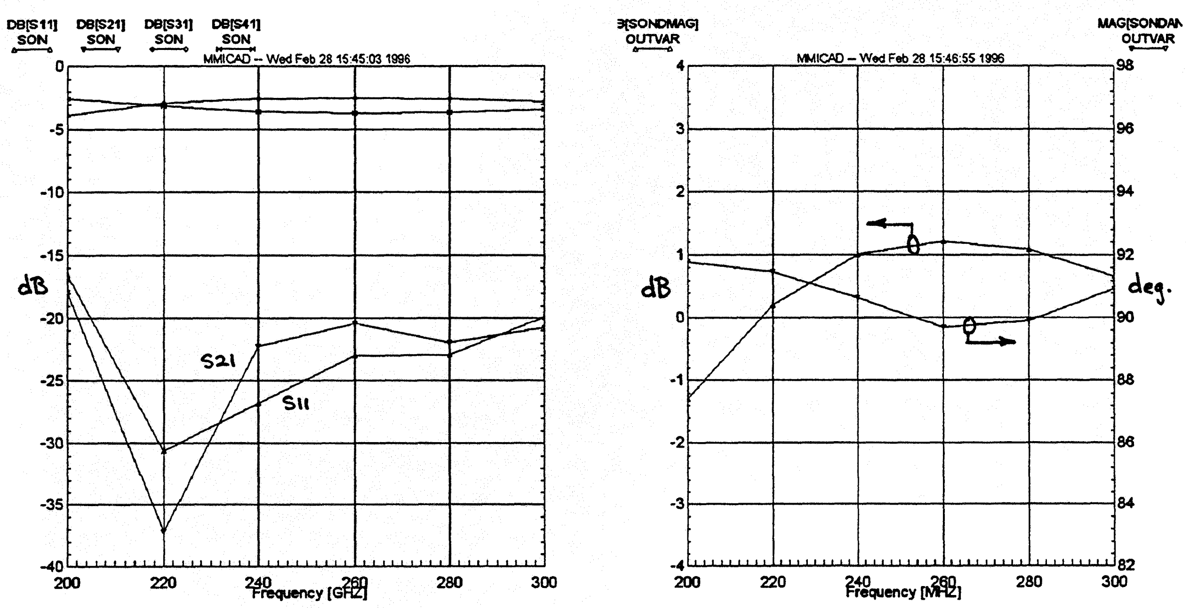

Fig. 11. S-parameters of the quadrature hybrid from Sonnet *em* simulation.

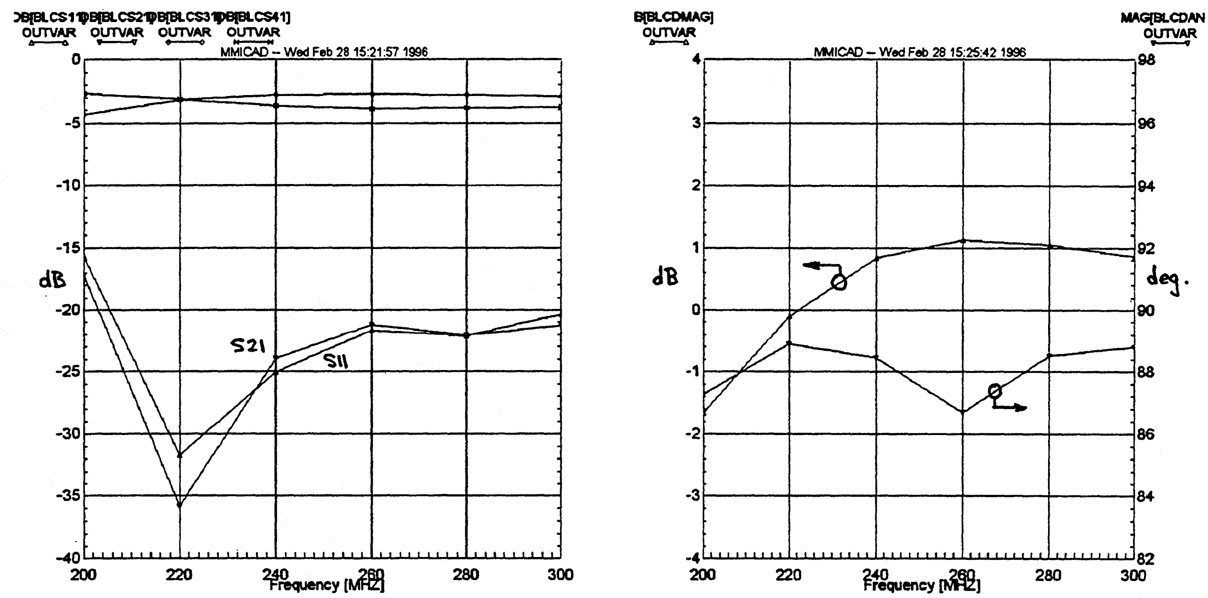

Fig. 12. S-parameters of the 1000 x scale model of the quadrature hybrid.

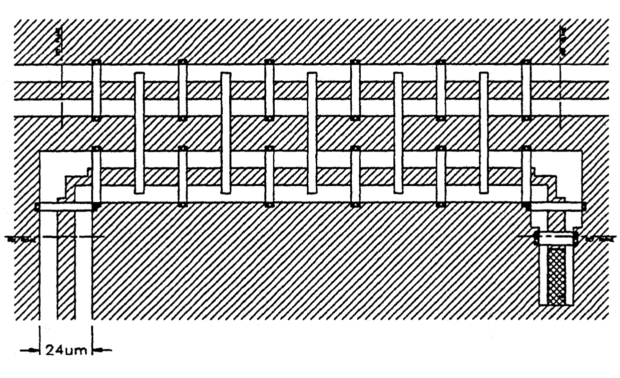

Fig. 13. The LO coupler. The five long vertical strips couple capacitively between the two CLCPW's.

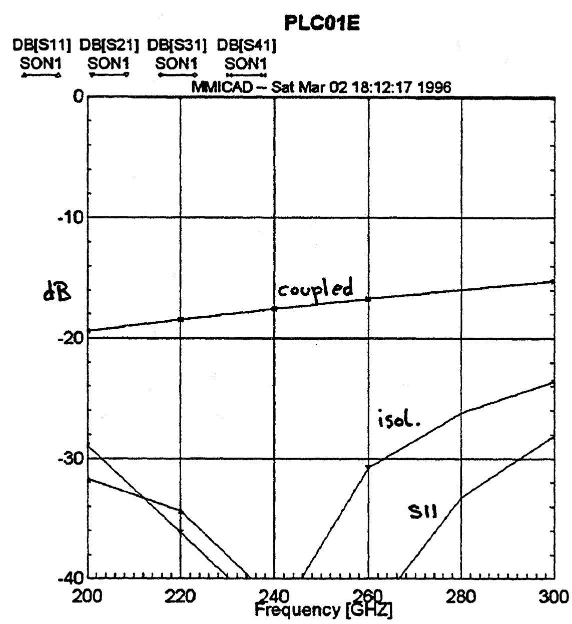

Fig.14. S-parameters of the LO coupler from Sonnet *em* simulation.

LO Power Splitter

The LO power-splitter, shown in Fig. 15, is based on the standard Wilkinson configuration, and was also designed using Sonnet *em* and MMICAD. Ideally this type of circuit requires a lumped resistor connected between the output ports to absorb the difference signals between those ports. The 100-ohm resistor in the present design is not electrically short, which accounts for the relatively poor output match and isolation, shown in Fig. 16. The input return loss and isolation are ≥ 16 dB, while the output return loss ≥ 13 dB from 200-300 GHz. The critical parameters, equal phase and amplitude at the output ports, are assured by the symmetry of the circuit.

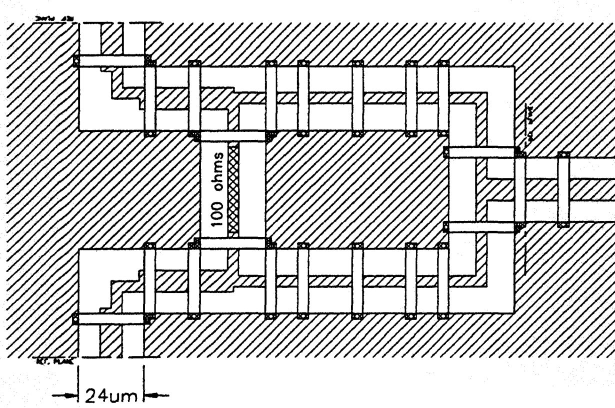

Fig. 15. The LO power splitter.

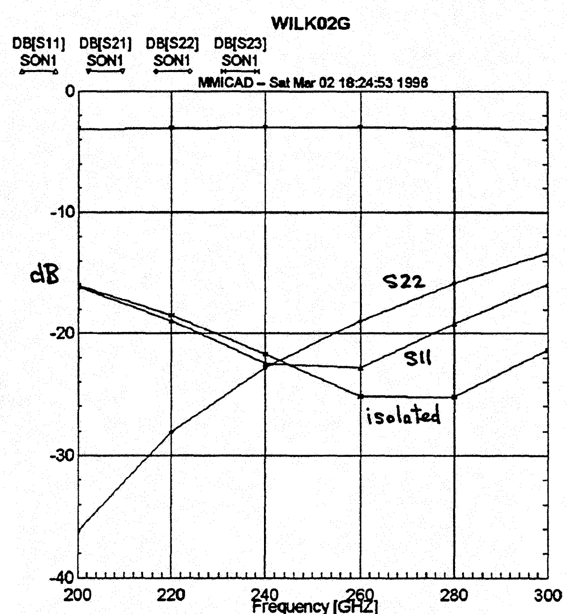

Fig.16. S-parameters of the power splitter from Sonnet *em* simulation.

The Case for Balanced Mixers

The LO power is usually coupled into a millimeter-wave SIS mixer using a directional coupler or beam splitter. If the signal path loss through the LO coupler is to be kept small, the LO loss must be substantial, and is typically 15-20 dB. In addition to wasting most of the LO power, noise from the LO source in the signal and image bands is coupled into the mixer. Depending on the nature of the LO source, its (sideband) noise temperature may be room temperature or higher. If the LO source has an effective noise temperature of 300 K at the sideband frequencies, then a 15-20 dB beam splitter will contribute 10-3 K in each sideband at the input of the mixer, which may be comparable with the intrinsic noise temperature of the receiver itself. We have observed with some LO sources a considerably higher excess sideband noise; some frequency multipliers in the 200-300 GHz range have been observed to contribute as much as 50 K of sideband noise at the input of the mixer.

A balanced mixer eliminates both these shortcomings. It has a separate LO port with efficient coupling (but two mixers to drive), so the required LO power is reduced by 12-17 dB relative to the simple single-ended mixer. Sideband noise is reduced by an amount dependent on the accuracy of the 180° phase shift and amplitude balance through the mixer.

Types of Balanced Mixer

Many types of balanced mixer exist. The most common at radio frequencies is the transformer type. In waveguide, the magic-T balanced mixer, was once common, although it has now largely been replaced by the planar hybrid-ring and quadrature hybrid types. The circuit of the quadrature hybrid type is shown in Fig. 17. The signal and LO are coupled to the individual mixers through the quadrature hybrid. A 180° IF hybrid combines IF output of the two mixers so that all the down-converted signal appears at one output port, and all the LO sideband noise appears at the other (a convenient scheme for measuring LO sideband noise).

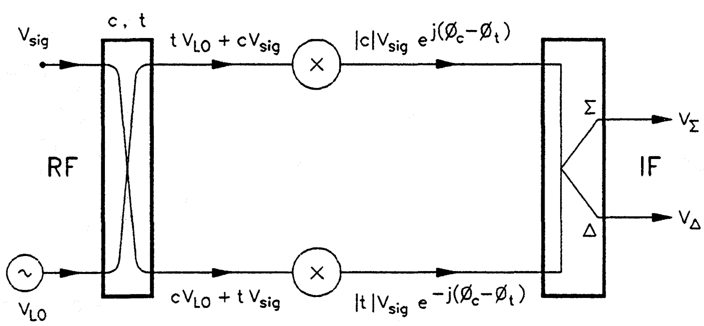

Fig. 17. Circuit of a balanced mixer consisting of a quadrature hybrid, an identical pair of simple mixers, and a 180° IF hybrid.

Amplitude and Phase Requirements

The isolation of a balanced mixer depends on the amplitude and phase balance of the components. The signal flow through the mixer is indicated in Fig. 17, where the mixers are assumed for convenience to have unit conversion gain. Using an analysis similar to that used above in the case of the image separating mixer, it is possible to calculate the worst-case isolation for given amplitude and phase uncertainties in the components. The results are approximately the same as shown in Fig. 8 for the image rejection of the image separating mixer. In the case of the balanced mixer, the vertical axes in Fig. 8 give the isolation in dB, the amplitude imbalance is the signal path imbalance, and the phase imbalance is (twice the phase imbalance of the quadrature hybrid) + (the phase imbalance of the isolated port of the 180° hybrid). If the mixers have unequal conversion loss, the difference can be included in c and t. From Fig. 8 it is clear that to ensure 20 dB image rejection, the amplitude imbalance must be < 1.7 dB or the phase imbalance < 12°. For 10 dB image rejection, the amplitude imbalance must be < 5.7 dB or the phase imbalance < 35°. Again, the surprisingly large allowable asymmetry is a result of dealing with sums and differences of complex amplitudes rather than powers.

A Balanced Mixer for 200-300 GHz

A balanced mixer is considerably simpler than an image separating mixer, and can be designed using the same quadrature hybrid and SIS mixers. As no resistive terminations are required on the substrate, fabrication is also less complex. Fig. 18 shows a balanced mixer which uses the components described earlier in this paper.

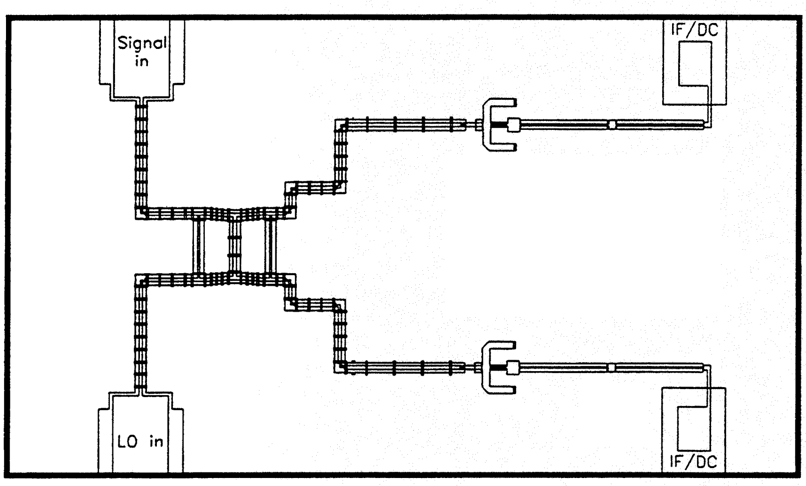

Fig. 18. Main substrate of the balanced mixer, showing the quadrature hybrid and two SIS mixers.

Discussion

It is apparent that construction of single-chip image separating and balanced SIS mixers is now practical. There has been some concern that the tolerances on critical parameters in today's Nb foundries may not be good enough for circuits of this complexity. However, by far the most critical components in these circuits are the SIS junctions and their immediate matching circuits; if these can be made sufficiently reproducibly, which appears now to be the case, then we can expect an acceptable yield of the more complex circuits. It is not known yet whether the relatively large area of each circuit will increase the probability of a significant fabrication defect in any given mixer to an unacceptable level. Considering the phenomenally low defect rate in the Si microcircuit industry, this should not be a fundamental limitation.

If the image separating mixer turns out to be practical, it is only a small additional step to use balanced mixers within the image separating mixer — a balanced image separating mixer. This will be relatively immune to LO noise, and will require a LO power level 14 dB lower than a single simple SIS mixer using a 20 dB LO coupler.

Acknowledgments

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[6] MMICAD is a microwave integrated circuit analysis and optimization program, and is a product of Optotek, Ltd., Ontario, Canada K2K-2A9.