Double-Double Balanced MMIC Mixer

Coplanar waveguides, slot lines and coplanar strips are combined to realize a MMIC double-double balanced mixer (DDBM) in which all circuitry is on the top side of the substrate and no via holes are required, in what is believed to be the first multioctave bandwidth, planar diode MMIC DDBM.

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Double-double balanced mixers (DDBM) are an important class of mixer because they facilitate overlapping RF and IF bandwidths while still providing RF to IF, LO to RF and LO to IF isolation. Most DDBM designs require separate RF, LO and IF baluns and eight diodes. Such a mixer is very difficult to realize in planar form. Techniques [1, 2] such as orthogonal substrates, twisted Duroid structures and other means that are not easily amenable to MIC or MMIC fabrication have been used in previously reported DDBMs (Figure 1).

Double-double balanced mixers are important because they separate RF, IF and LO signals even when their bandwidths overlay.

The equivalent circuit of a dual ring DDBM is shown in Figure 2. It consists of a LO/RF 180 degree hybrid represented by two sets of appropriately phased ideal transformers, 8 diodes and an IF balun shown as a single transformer. The diode RF and LO voltages are shown as solid and broken

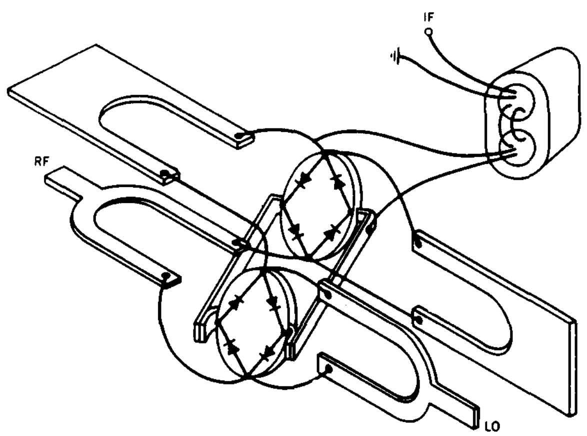

Figure 1. Example of a typical non-planar DDBM realization. Structures such as these are very difficult to realize in a MMIC format.

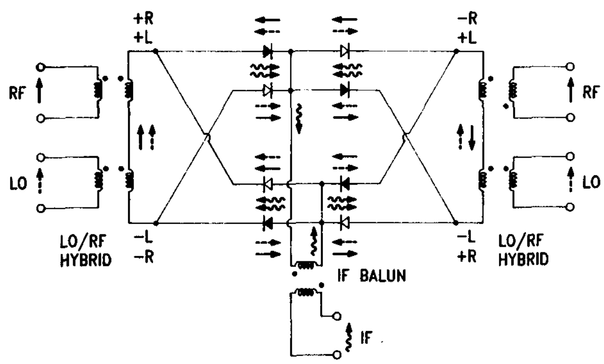

Figure 2. Equivalent circuit of a dual ring double-double balanced mixer.

arrows respectively. The resulting IF currents shown as wiggly arrows are focused upon the IF balun in a push pull format while the RF and LO voltages cancel providing RF to IF and LO to IF isolation. The IF balun converts the push pull IF currents to a single ended output.

This MMIC mixer employs a new mix of slot line, coplanar waveguide and coplanar strips.

The MMIC mixer described in this paper employs a novel mix of slot line, coplanar waveguide (CPW) and coplanar strips (CPS) and eight GaAs Schottky diodes and is fabricated on a 16 mil thick GaAs substrate without the use of via holes. The resulting mixer, although somewhat large with an area of 180x240 mils, is low in cost to fabricate. A MIC realization of the structure is also quite practical since the only components that must be attached to the substrate are the eight diodes.

The DDBM was carefully modeled and the harmonic balance method was used to assess the conversion loss, VSWR, isolation and spurious behavior of the mixer as a function of frequency and LO drive level. Circuit element values were manually adjusted to enhance performance, but mathematical optimization was not feasible because of the length of time required by each analysis pass. The resulting DDBM operated over a RF bandwidth of 6 to 20 GHz, a LO bandwidth of 8 to 18 GHz and an IF bandwidth of 2 to 7 GHz with conversion loss ranging from 6.2 to 9.8 dB. RF to IF, LO to RF and LO to IF isolations were 25 dB, 23 dB and 20 dB respectively. The measured and simulated performance were in reasonable agreement.

Manual optimization of circuit elements was used, because the mathematical process took too long.

Mixer Circuit Design and Modeling

The DDBM is composed of an 180 degree hybrid, an IF balun and eight GaAs Schottky diodes. A photograph of the mixer is shown in Figure 3.

The 180 hybrid operates at the sum port from 2-22 GHz and at the difference from 5-20 GHz.

The 180 degree hybrid employs CPW, CPS and slot lines and operates over a sum port bandwidth of 2 to 22 GHz and a difference port bandwidth of 5 to 20 GHz. The hybrid design builds upon previously reported uniplanar technology [3, 4]. The signal driving the sum port is delivered via a 50 ohm CPW line to a pair of three section transformers, each composed of two uncoupled slot line sections and a CPS section in cascade.

Each transformer is designed to transform a 50

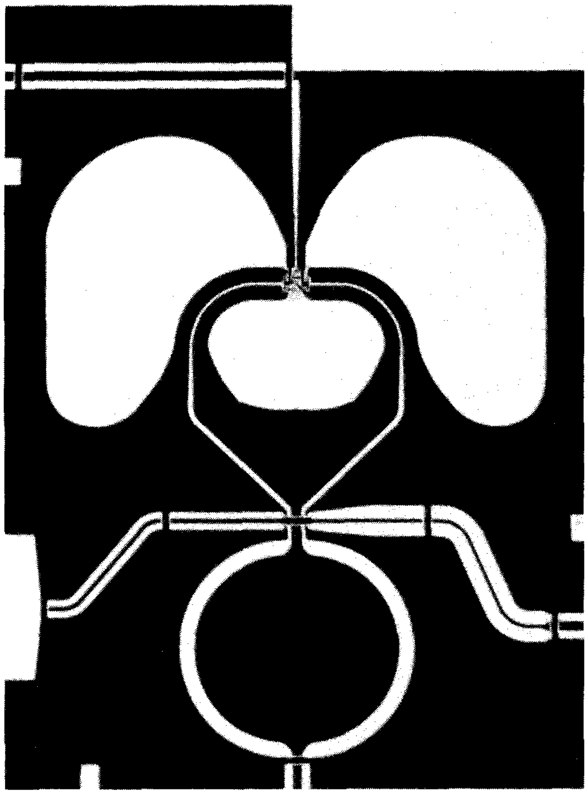

Figure 3a. Photograph of double-double balanced mixer chip showing RF, LO 180 degree hybrid, IF balun and dual diode ring. Chip size is 180x240x16 mils.

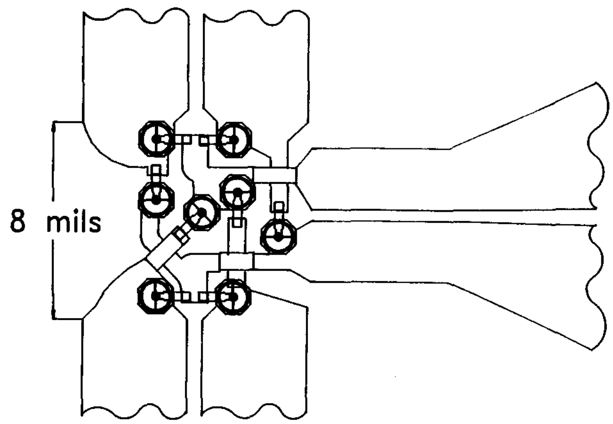

Figure 3b. Detail of dual diode ring showing connections to the RF-LO Hybrid and IF Balun.

Ohm load at the CPS end to 100 Ohms at the slot line end where it is paralleled with another transformer properly terminating the sum input CPW. The difference port input CPW, the open circuited CPW stub, the circular slot line sections and the output slot lines together form a fourth order Marchand balun [5] covering the 5 to 20 GHz band.

Odd and even mode equivalent circuits of the 180 degree hybrid are shown in Figure 4. If the sum port is excited, the signal is delivered to each output port in phase, without delivering energy to the difference port. Exciting the difference port results in out of phase signals delivered to the output ports. The Marchand baluns are clearly shown in the odd mode equivalent circuit.

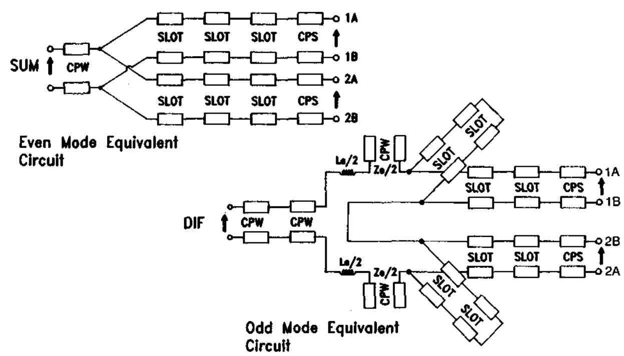

Figure 4. Odd and even mode equivalent circuits of the 180 degree hybrid.

Inspection of the electric field vectors shows that signals exciting the sum port appear at the output port in phase, while signals exciting the difference port arrive at the output ports out of phase. This yields a 180 degree hybrid with CPN inputs and CPW outputs. A layout of the hybrid is shown in Figure 5 with its equivalent circuit in Figure 6,

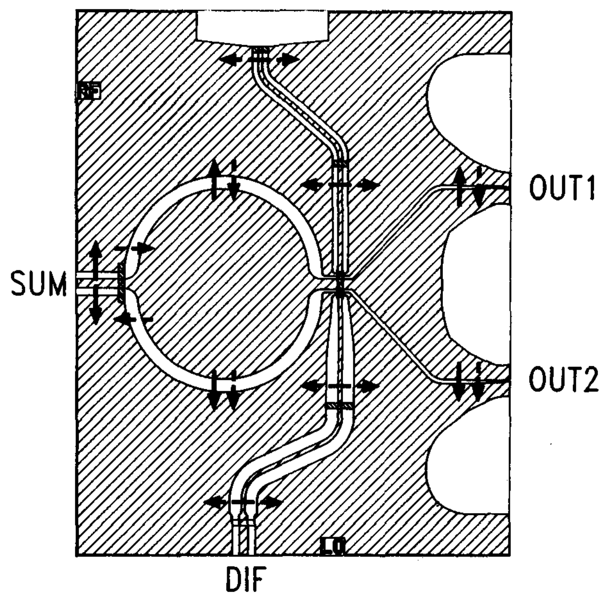

Figure 5. Layout of the 180 degree hybrid composed of CPW, CPS and slot lines.

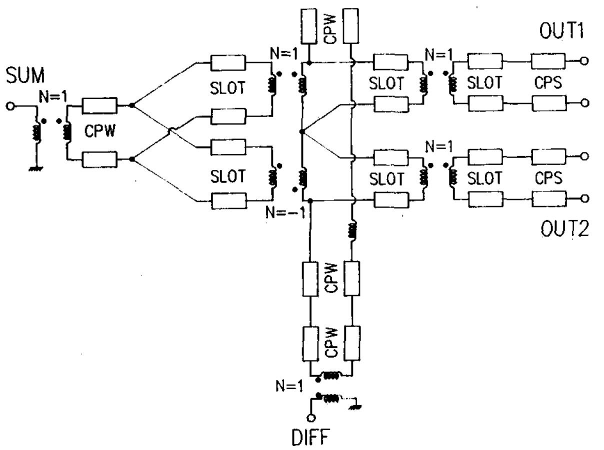

Figure 6. Equivalent circuit model of 180 degree hybrid is obtained by super-position of the individual odd and even mode equivalent circuits of the device.

which shows the Marchand Balun composed of the DIF port CPW transformer section, the CPW open stub and the slot lines to the left and right of the junction.

Signals incident on the sum port (solid arrows) in Figure 5 are delivered in phase at the output ports while signal incident on the difference port (broken arrows) are delivered out of phase. The difference port is isolated from the sum port by the even mode short circuit provided by the air-bridge near the sum port.

The simulated performance is shown in Figure 7, which included reasonably accurate CPW, CPS and slot line models but ignored junction discontinuities. Return loss was 12 dB minimum on all ports, coupling was 3.4+0.25 dB and phase difference was 180+2.2 degrees across the 5-20 GHz band. The simulation was accomplished by adding slot line and CPW models to the Libra (trademark of EEsof Inc.) circuit simulator.

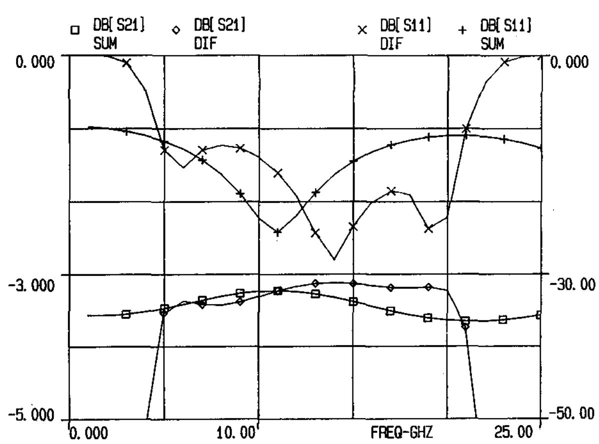

Figure 7. Computed performance of 180 degree hybrid.

A simulation was made by adding slot line and coplanar waveguide models to Libra[TM].

The IF balun consists of a CPW to slot line transition followed by a slot line to CPS transition [6]. This structure is shown in Figure 8.

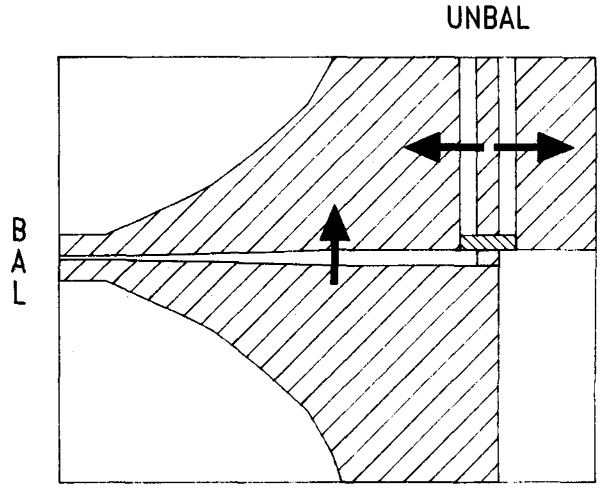

Figure 8. The IF balun structure is formed by transitions from CPW to slot line to CPS.

Schottkys have 3 micron diameter, cutoff frequency over 1000 GHz.

All signals are delivered to the diodes on balanced CPS lines. The diodes have 3 micron diameter Schottky contacts air-bridged to the desired point of connection and exhibit a cutoff frequency in excess of 1000 GHz.

The complete mixer, shown schematically in Figure 9, was analyzed using the Libra harmonic balance simulator and element values were adjusted for best conversion loss. Agreement between measured and modeled conversion loss was within 1.5 dB at each frequency. This is reasonable agreement between theory and experiment, considering the fact that transmission line discontinuity effects were ignored and that the analysis used a harmonic number of five, requiring the simulation to be accurate to at least 100 GHz.

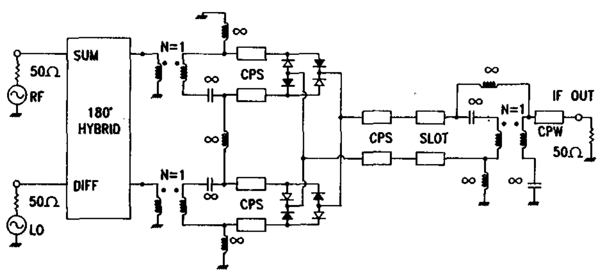

Figure 9. Equivalent circuit used for harmonic balance analysis showing diode connections and infinite value L's and C's added to setup proper dc initial conditions.

Since RF, LO and IF overlap in the mixer's 6-20 GHz test, inherent isolation must be employed to reject undesired signals.

Fabrication and Measured Performance

The design requires no via holes, hence no backside processing.

The MMIC was fabricated on 16 mil thick GaAs substrates. A simple MBE material structure, consisting of a 1200 Angstrom thick N layer doped $2x10^{17}/cm3$ and an 1800 Angstrom thick N+ layer $2x10^{18}/cm3$ grown on a semi-insulating GaAs substrate, was used to fabricate the MMIC mixer. Standard front side MMIC processes were used. The Schottky dot was formed using titanium-platinum-gold (Ti-Pt-Au) first level metal. Ideality constants of 1.17 or less were routinely obtained. Since no via holes were required by the design, no backside processing was necessary. This has reduced process complexity and significantly improved yields. Figure 10 shows a cross-sectional plan for a typical Schottky diode fabricated using this process. The 2000 angstrom silicon nitride (Si_3N_4) passivation layer is omitted from the drawing for simplicity.

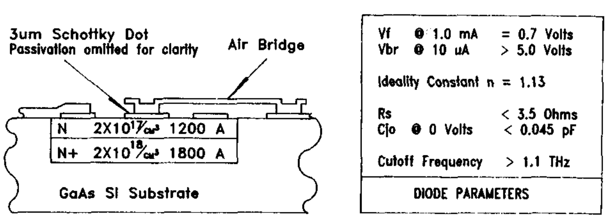

Figure 10. Cross-section of Litton MMIC Mixer Diode showing the air bridge connection to the 3 micron Schottky dot.

The chips were mounted in a CPW test fixture composed of tapered CPW lines on 20 mil alumina substrates with K series coaxial launchers. The mixer's measured RF bandwidth was 6 to 20 GHz, its LO bandwidth was 8 to 18 GHz and its IF bandwidth was 2 to 7 GHz. Since the RF, LO and IF bands overlap there is no possibility of filtering to eliminate undesired signals and the mixer's inherent isolation must be depended upon to reject these signals.

The RF to IF, LO to RF and LO to IF isolation are 25 dB, 23 dB and 20 dB respectively. The mixer's conversion loss ranged from 6.2 to 9.8 dB. The RF input power for 1 dB compression was +8.5 dBm and the third order input intercept point was +20 dBm. Worst case VSWR was 3:1 at any port. These data are tabulated in Table 1.

RF Bandwidth	6-20 GHz
LO Bandwidth	8-18 GHz
IF Bandwidth	2-7 GHz
RF Port VSWR	2.5:1
LO Port VSWR	3.0:1
IF Port VSWR	3.0:1
LO Power	+17 dBm
Conversion Loss	9.8 dBm max., 7.5 dB typ.
LO-RF Isolation	23 dB min.
LO-IF Isolation	20 dB min.
RF-IF Isolation	25 dB min.
RF Pin @ 1 dB Comp.	+8.5 dBm
RF Input 3IP	+20 dBm

Table 1. Summary of MMIC Mixer Performance

Acknowledgment

The authors wish to acknowledge John Archer who designed and characterized the diodes, the Litton Solid State Division Foundry staff who processed the wafers, Dr. Paul Bauhahn of Honeywell's System and Research Center and Dr. Morten Maesel currently with ST Microwave, who both provided a great deal of technical insight into the operation of diode mixers.

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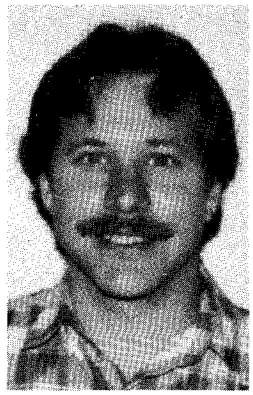

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During 1978-1979 he did research in the area of applications of microwave in nondestructive evaluation of material properties. He joined TRW microwave in 1980, as a Design Engineer and worked on the development of high power PIN limiters, 2-18 GHz Schottky and Planar Tunnel Detectors, PIN switches and mixers. He joined Varian Solid State Microwave Division in October 1981 where he designed balanced MIC amplifiers covering the 2-6 GHz, 6-13 GHz bands, and also 0.5-2.5 GHz and 2-6 GHz feedback amplifiers.

In 1985, he began the development of MMIC devices at Varian Solid State Microwave Division. He has been involved in developing a range of 1-40 GHz low noise amplifiers, 1-40 GHz mixers, a series of 2-20 GHz distributed amplifiers and millimeter-wave amplifiers. Currently he is the MMIC Product Line Manager of the Litton Solid State Division (formerly Varian SSMD).