Double Balanced Star Mixer

This star configuration MMIC mixer extracts the IF signal at a virtual ground for both LO and RF signals, eliminating a diplexer. This and on chip matching affords a 6 GHz simultaneous IF bandwidth.

Joseph Staudinger
Motorola Semiconductor Products Sector
Tempe, Arizona
Mike Friesen
Motorola Government Electronics Group
Chandler, Arizona

Both military and telecommunication systems require mixers which occupy smaller areas, cost less and exhibit higher levels of performance and reliability than can be realized with hybrid monolithic integrated circuits (MICs), requiring a monolithic microwave integrated circuit (MMIC) approach. However, previous diode MMIC mixers have used topologies typical of hybrid mixer circuits [1-3]. Figure 1 illustrates this typical circuit wherein four diodes arranged in a ring configuration are connected to two baluns, one balun each for the LO and RF signals. Matching elements are often required between baluns and diodes to achieve the best performance.

In the MMIC implementation, the baluns can be implemented using passive approaches (distributed or lumped elements) or by active methods.
Functionally, the two baluns establish phase/amplitude balance for the LO/RF signals. The Schottky diodes generate mixing action due primarily to their non-linear voltage-current characteristics. The baluns function to generate balanced RF and LO signals which are then impressed with prescribed amplitude/phase characteristics across each diode. This results in inherent isolation between

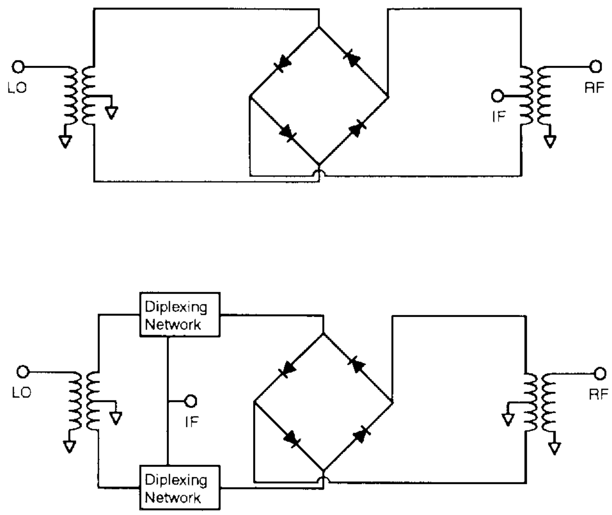

Figure 1. Most MMIC diode mixers are based on four diodes arranged in a star configuration which are connected to two baluns. The IF signal can be extracted by either of two means, a) the fourth port of the baluns, and b) by diplexing the IF from either the LO or RF signal.

LO and RF ports due to the circuit topology which causes signal cancellation.

Depending on the frequencies of the LO and RF signals, the IF signal is usually extracted by one of two methods, either from the fourth port of one balun as shown in Figure 1a, or by diplexing the IF from either the LO or RF as shown in Figure 1b. With the first method, extracting the IF signal with a balun is well suited when the frequencies of the three signals fall within the bandwidth of the balun. When this is not the case, such as when the IF signal is considerably above or below the other two, the second method, diplexing, may be more suitable. In this case, the baluns need cover only the frequency range of the LO and/or RF.

But these topologies are unsuitable when the IF frequency is not sufficiently separated from, or extends into the RF/LO frequency range. Then diplexing the IF from the LO/RF signals is impossible. While theoretically the IF could be obtained at the fourth port of the LO or RF balun, which has a response similar to a center tapped transformer, the required bandwidth for the balun may be too great for practical realization on MMIC.

For example, consider a mixer with an LO frequency range of 20 to 26 GHz, an RF range of 12 to 18 GHz, and an IF frequency range of 4 to 12 GHz. Clearly, the IF signal cannot be diplexed, and extracting the IF from the fourth balun port would require the realization of a balun with a 6.5:1 bandwidth (4 GHz to 26 GHz), impractical on MMIC.

We have addressed this situation with a mixer which utilizes four diodes arranged in a star configuration, with all circuitry contained on a single MMIC die. This mixer topology is similar in form to hybrid star mixers [7], although unlike most hybrid designs, it is realized completely in a planar media (MMIC) [11].

Compared to ring type mixers, extracting the IF signal is simplified for the star configuration, since the IF node is a virtual ground to both LO and RF signals, thereby obviating the necessity for diplexing, although some filtering at the IF port may be desired to improve LO/RF to IF isolation. An additional benefit inherent in the topology (due to the high degree of symmetry) is the potential of very high port to port isolation.

Circuitry

The star mixer is shown schematically in Figure 2 and consists of three broadband baluns, an in-phase power divider network, and four Schottky diodes arranged, as evident in the Figure, in a star configuration. Matching circuity, not shown, can be included between diodes and baluns as well as on the IF port to improve conversion efficiency and minimize LO drive requirements.

The LO signal is applied at the input of a balun while the RF signal is applied at the power divider input port. Alternatively, these two ports can be interchanged although practical MMIC realization

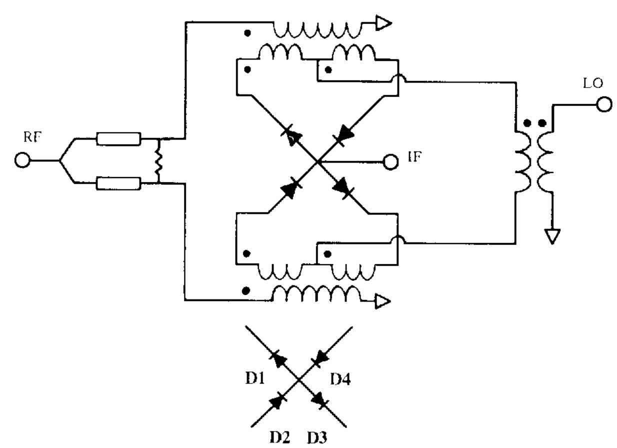

Figure 2. The new mixer is based on a topology where the four diodes are arranged in a star configuration.

favors injecting the RF with a power divider. The IF signal is extracted at the center of the diodes.

The operation of the mixer can be analyzed using the phase state method described by Hallford [6] to determine relative phase states of the LO, RF, and IF signals throughout the circuit. This method is used both to verify that the topology is correct as well as to examine its performance potential. In particular, conversion and isolation characteristics are easily examined this way. In the analysis, the central diode node (IF port, Figure 2) is defined as a reference for all voltage phases.

Conversion characteristics can be examined by computing the IF components developed in each diode. Referring to Figure 2, assume LO and RF of arbitrary phase are applied at each port (Figure 2) of the mixer. The RF signal applied at the power divider port is split into two equal amplitude and identical phase signals. Thus, RF signals of equal amplitude and phase are incident onto the two central baluns which are connected to four diodes.

An observation of the resultant voltages indicates two sets of diodes each exhibit identical phase. (i.e., diodes D1 and D2 as well as diodes D3 and D4). Therefore, a virtual ground develops at the center of the diode star, which is also the IF port. By noting the signal paths through each balun and power divider to the diodes, the voltage phase relationships shown in Table 1 are obtained.

Similarly, when the LO signal is applied at the input port of the far right balun (Figure 2), the signal is split in amplitude with a relative phase displacement of (180°) from each other. Due to the central baluns voltages at the LO frequency develop across each diode. Again, two sets of diodes exhibit identical phase (i.e., diodes D1 and D4 as well as diodes D2 and D3). Similarly, a virtual ground develops at the center of the diode star.

The relative phase of the LO and RF signals at each diode are tabulated in Table 1. The relative phase of the IF signal can be obtained from the expression:

Eq. 1.

$$\Phi_{IF} = \Phi_{LO} - \Phi_{RF} - \Phi_D$$

where

Φ_{IF} is the relative phase of the IF signal

Φ_{LO} is the relative phase of the LO signal,

Φ_{RF} is the relative phase of the RF signal, and

Φ_D represents the diode polarity.

Reference node is the IF port

Phase Vector	D1	D2	D3	D4
Φ_{LO}	0	180	180	0
Φ_{RF}	0	0	180	180
Φ_D	0	180	0	180
Φ_{IF}	0	0	0	0

Table 1. Relative Phase Of LO, RF, and IF signals.

The advantage of the STAR mixer is that the IF is taken from a node which is a virtual null for the RF and LO signals, obviating the need for a diplexer.

As seen in Table 1, IF components produced in each diode exhibit similar phase and therefore constructively combine at the IF port. Furthermore, the LO and RF signals vectorially cancel at the IF port, creating a virtual ground which isolates the IF port from the other two ports. For this reason the IF signal can be extracted at this node without any need for diplexing it from the LO or RF frequencies. A similar analysis can be performed for the case of up conversion, for which IF components produced in each diode again combine at the IF port. Hence, when the mixer is operated in down conversion, the terminating impedance presented to the up converted signal will effect mixer performance.

Similarly, the isolation between various ports of the mixer can be determined. The isolation between the LO/RF to IF port is due entirely to signals vectorially canceling at the IF port (Table 1). Accordingly, the amplitude/phase response of the three baluns and power divider largely determines isolation to the IF port. Isolation between the LO and RF ports is obtained from the isolation characteristics of the two central baluns. Additional isolation results from the power divider and LO balun.

By performing this analysis, it is seen that the star configuration satisfies three important criteria, a) isolation is achieved between all ports, b) the IF components produced in each diode add constructively at the IF node, and c) the IF port is a virtual ground to LO and RF signals.

Practical Circuitry

A MMIC mixer was designed to translate an RF signal at 12-18 GHz with a 20-26 GHz LO signal to an IF in the range of 6-12 GHz with an LO drive level of 12-14 dBm. Key design goals included minimizing conversion loss to approximately 7 dB, designing the circuit to achieve full functionality on the initial design pass, and realizing the complete MMIC mixer on a single MMIC die. Die dimensions chosen for the mixer are 100 x 80 x 3.5 mils.

The mixer designed has an RF of 12-18 GHz, an LO of 20-26 GHz and a simultaneous IF bandwidth of 6 GHz.

To implement the mixer monolithically on a reasonably small sized die, the required baluns and power divider sub-circuits must be compact (occupy limited real estate) and exhibit good performance through 26 GHz. To limit needed area, passive topologies were selected for each sub-circuit. Due to the nature of the mixer topology, each sub-circuit was designed independently and then integrated to form the final circuit.

This allowed optimizing performance, such as minimizing the return loss and insertion loss of each sub-circuit independently using linear analysis methods. Thus layout considerations and appropriate MMIC models for inductors, capacitors, resistors, etc., could also be included in the linear simulations. This design methodology proved valuable in that much of the mixer could be designed using linear simulations.

After the design of each sub-circuit was completed (including layout considerations), the entire circuit (less all matching circuitry) was simulated using harmonic balance. At this point, large signal simulations were performed to determine diode impedance levels to aid in developing optimal matching circuits. Once developed, these networks were largely integrated into the baluns to minimize real estate needs further as well as to improve the overall bandwidth performance.

Large signal circuit simulations were useful in the design of terminations for high frequency components generated in the diodes.

Large signal simulations also proved valuable in evaluating the effects of terminating higher frequency components generated in the diodes. In this mixer, these components are effectively terminated by internal matching structures placed between diodes and central baluns as well as the matching structure at the IF port. Some (very) limited large signal optimization using harmonic balance methods was performed on these terminations. The design of the power divider and balun are based on linear techniques.

Power Divider

Based on previous power divider designs [4,5,8], a lumped structure was chosen for the power divider network (Figure 3). The impedance transformers are realized as minimum element bandpass structures. This topology was chosen since it easily achieves an insertion loss of about 0.5 dB with good return loss over more than an octave. Component values are quite reasonable for MMIC implementation even for operation to 26 GHz.

Lumped element power dividers were used to conserve space in the MMIC circuit.

The components were realized monolithically as MIM capacitors, spiral inductors, and some high impedance transmission lines. The low insertion loss in the divider is highly desirable since this loss contributes directly to mixer conversion loss. Design efforts concentrated on layout aspects along with circuit optimization to minimize insertion loss.

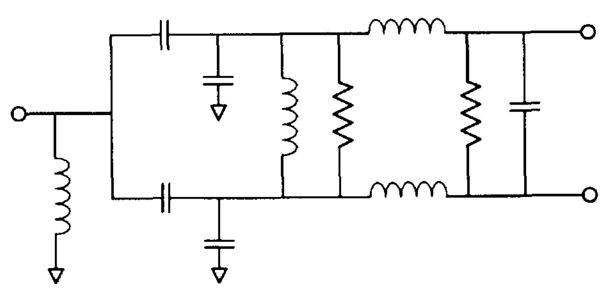

Figure 3. The power divider was realized using a lumped element topology based on a minimum element bandpass structure.

180 Degree Hybrids

The lumped element 180 degree hybrid uses the high pass/low pass equivalent circuits instead of distributed transmission lines.

The baluns were realized using passive elements in a circuit topology consisting of high/low pass filter structures similar to that reported by Parisi [9] and Staudinger [10]. A generalized lumped element schematic for the hybrid is shown in Figure 4.

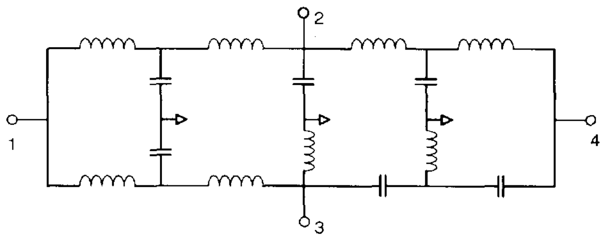

Figure 4. The 180 degree was implemented using fourth order high/low pass filter structures.

The operation can be evaluated by examining the S-parameters which are given by:

Eq. 2.

$$S = \begin{vmatrix} 0 & -j.707 & -j.707 & 0 \\ -j.707 & 0 & 0 & -j.707 \\ -j.707 & 0 & 0 & j.707 \\ 0 & -j.707 & j.707 & 0 \end{vmatrix}$$

Functionally, this network is similar to an ideal transformer in that opposite ports are isolated from each other, i.e., port 1 is isolated from port 4, and port 2 from port 3. The network provides equal power division with either zero or 180 relative phase displacement. A 180 degree phase differential is obtained due to S43 and S42, while zero phase differential results between S21 and S32.

Circuit component values were derived using network synthesis techniques. Considering the bandwidth needed (12 GHz to 26 GHz), component values were synthesized to approximate a Chebychev response in both amplitude and phase characteristics. Considering the required bandwidth and a generalized low pass prototype network centered at one ohm impedance and a frequency of 1 Hz, poles were selected in the reflection coefficient at 0.77 Hz and at 1.35 Hz. This results in an overall bandwidth of about 2.2:1, sufficient to cover a 12 to 26 GHz bandwidth. Based on this constraint, element values were then extracted. The response for the unscaled prototype network based on ideal components is shown in Figure 5.

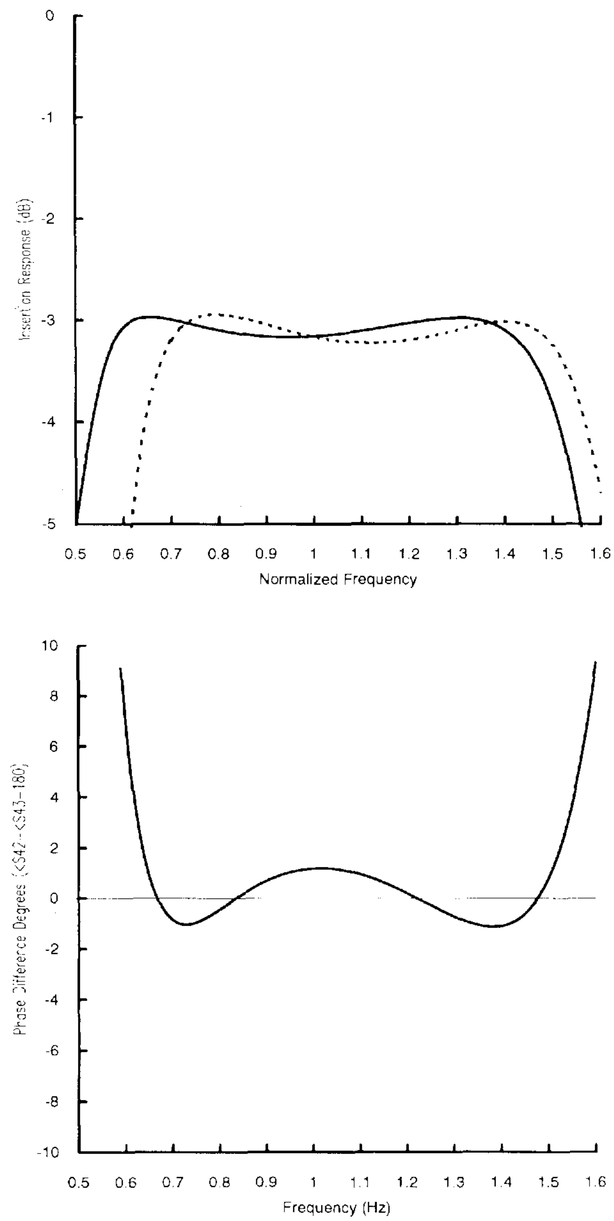

Figure 5. Response of low pass prototype 180 degree hybrid with a center frequency of 1 Hz and 1 ohm impedance. a) Insertion response of S21, S31, S42, S43. b) 180 degree phase response.

Both the desired amplitude and phase performance are achieved over the required bandwidth. The phase response for S42 and S43 has 180 degree phase differential with less than 1.5 degree error. Similar phase tolerance is achieved for the zero degree phase differential between S21 and S31 voltages.

For the intended design, these prototype element values were scaled in both frequency and impedance to cover a 12 to 26 GHz bandwidth and 50 ohms impedance. For MMIC realization, inductance values were implemented with airbridge spiral inductors and some high impedance transmission lines for smaller inductance values. All capacitances were realized as MIM structures. Some linear optimization of the balun was performed to include layout effects as well as appropriate MMIC models.

Schottky Diodes

Schottky diodes for the mixer had to be consistent with the standard MMIC processing method chosen. Based on previous efforts, geometrical parameters, such as finger width, length and number were chosen to maximize the cut off frequency. A large signal diode model was developed by measuring forward bias, DC, and microwave S-parameter measurements on a diode to determine it's electrical behavior.

Schottky diodes, constrained by the MMIC processing, had a cutoff frequency of 250 GHz and gave overall conversion loss of 7 dB.

From these measurements, reverse saturation current, ideality factor, parasitic series resistance, and capacitance-voltage characteristics were determined. This information allowed extracting a large signal diode model, which was utilized in a harmonic balance simulator. The current-voltage characteristics for the diode are shown in Figure 6. The diode exhibits a series resistance (RS) of about 7 ohms.

Similarly, capacitance-voltage measurements were made to determine diode capacitance model parameters such as zero bias capacitance and grading coefficient. The results indicate a 0.082 pF zero bias capacitance (Cjo). Accordingly, the diode exhibits a cutoff frequency of about 250 GHz, i.e. Eq. 3.

$$f_c = 1/(2 \text{ PI } R_s C_{jo})$$

Large Signal Design

To enhance mixer conversion characteristics, two sets of matching structures were included in the design. One matching network is placed between each diode and the central baluns. A second one is included at the IF port. These matching structures function to maximize power transfer of LO signal power into the diodes and thus minimize overall LO power drive requirements. Additionally, these matching networks terminate other frequency components which significantly affect conversion performance and other mixer characteristics.

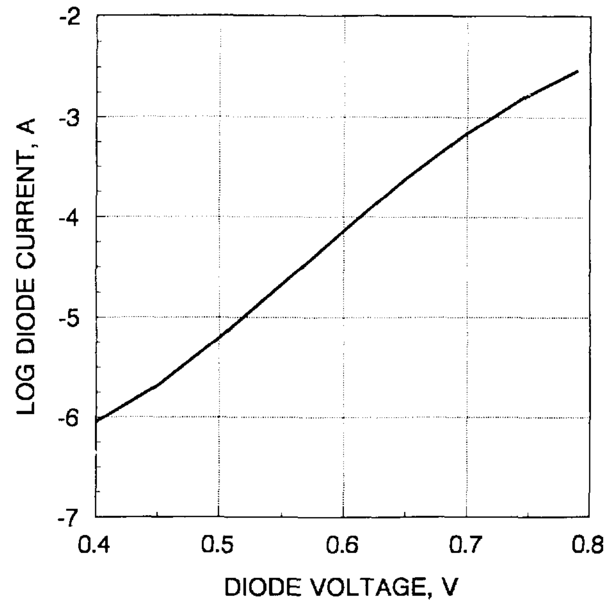

Figure 6. Measured current-voltage characteristics of the Schottky diode.

Due to the complexity of the circuit, large signal analysis methods (harmonic balance) were pursued in designing these networks. Since harmonic balance simulation methods are well suited for computing Fourier components of voltage and current throughout the circuit, signal components generated by the diodes are easily determined. Of particular interest are signal components at the LO and RF frequencies. To maximize power transfer, an effective diode impedance can be defined by considering the Fourier component of voltage and current of each diode. This impedance can be defined as follows:

Eq. 4.

$$Zd = V(f)/I(f)$$

Where V(f) and I(f) are Fourier frequency components of voltage and current, respectively.

Based on Equation 4, diode impedance levels were computed for both LO and RF frequency components. The results are shown below in Tables 2 and 3 for two LO drive levels corresponding to a delivered power (into the diode) of 1.2 and 4.0 dBm. In these simulations, RF power was maintained below -10 dBm.

Based on these results, lumped networks were initially designed to maximize power transfer of both LO and RF power into the diodes. These net-

Diode Impedance at LO Frequency		
LO Frequency (GHz)	P_D=1.2 dBm	P_D=4.0 dBm
20.0	16.9 - j96.8	24.7 - j88.5
21.0	17.7 - j91.5	24.3 -j84.3
22.0	16.4 - j87.3	22.2 - j81.0
23.0	14.9 - j84.1	20.4 - j78.6
24.0	13.4 - j81.3	18.8 - j76.5
25.0	11.9 - j78.7	16.9 - j74.9
26.0	9.3 - j77.0	13.6 - j74.4

Where P_D is the power deliver to the diode.

Table 2. Diode Impedance Level of LO Frequency Component.

Table 3
Diode Impedance Level at RF Frequency Component

Diode Impedance at RF Frequency		
RF Frequency (GHz)	P_D=1.2 dBm	P_D=4.0 dBm
12.0	60.0 - j152.8	57.7 - j137.3
13.0	57.5 - j143.1	56.1 -j128.5
14.0	53.0 - j135.8	53.3 - j122.4
15.0	50.6 - j126.7	52.2 - j114.8
16.0	50.3 - j117.2	52.1 - j106.7
17.0	48.9 - j109.4	50.7 - j99.9
18.0	48.7 - j106.9	51.0 - j97.9

Where P_D is the power delivered to the diode at an LO frequency of 22 GHz.

Table 3. Diode Impedance Level at RF Frequency Component.

works were then largely integrated into the central baluns to improve bandwidth performance and to further minimize required chip real estate.

A similar procedure was utilized on the IF port for matching purposes. However, in this case, a bandpass structure was selected to effect the termination of higher frequency components. After initial layout, the complete mixer was simulated using harmonic balance methods. However this allowed limited optimization due to the lengthy simulation time required.

MMIC Layout

A photograph of the completed MMIC mixer is shown in Figure 7. Via holes are used at several locations on the circuit to obtain the necessary grounds. Coplanar probe pads are included at the RF, LO and IF ports to allow on chip measurement and characterization. The chip dimensions are 100 x 80 x 3.5 mils.

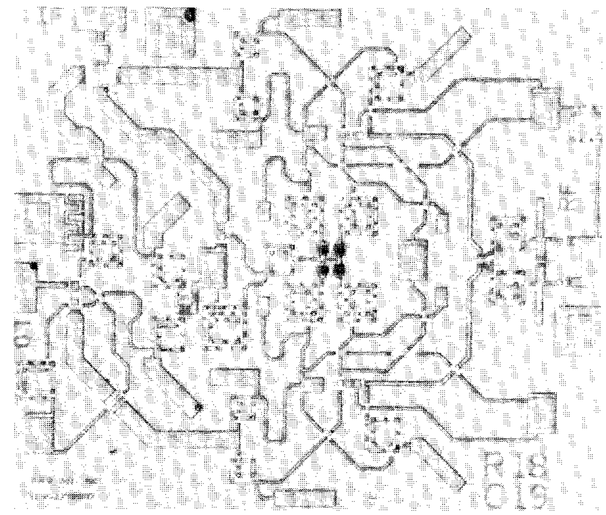

Figure 7. The complete double diode mixer was implemented on a single die with dimensions of 80 x 100 x 3.5 mils .

Measured Performance

Measured performance was consistent with theory.

Mixer performance characteristics were measured on circuits from the initial design pass using on-wafer probe equipment. Measured conversion loss performance is shown in Figure 8 for an LO drive level of about 14 dBm. The measured conversion loss is approximately 7 dB over an IF frequency range of 4 to 12 GHz. Beyond this range, the bandpass matching structure at the IF port significantly increases conversion loss. In general, circuit simulations agree well with the measured results.

The isolation performance shown in Figure 9 indicates an LO to IF isolation of generally better than 20 db while LO to RF isolation is about 30 dB. The LO to RF isolation obtained in this circuit is considerably below what was expected. The difference is attributed to a layout problem whereby one transmission line in the central baluns was inadvertently made to short. This resulted in phase/amplitude imbalance which degraded isolation. Additionally, some crossovers of LO and RF transmission lines also reduced isolation.

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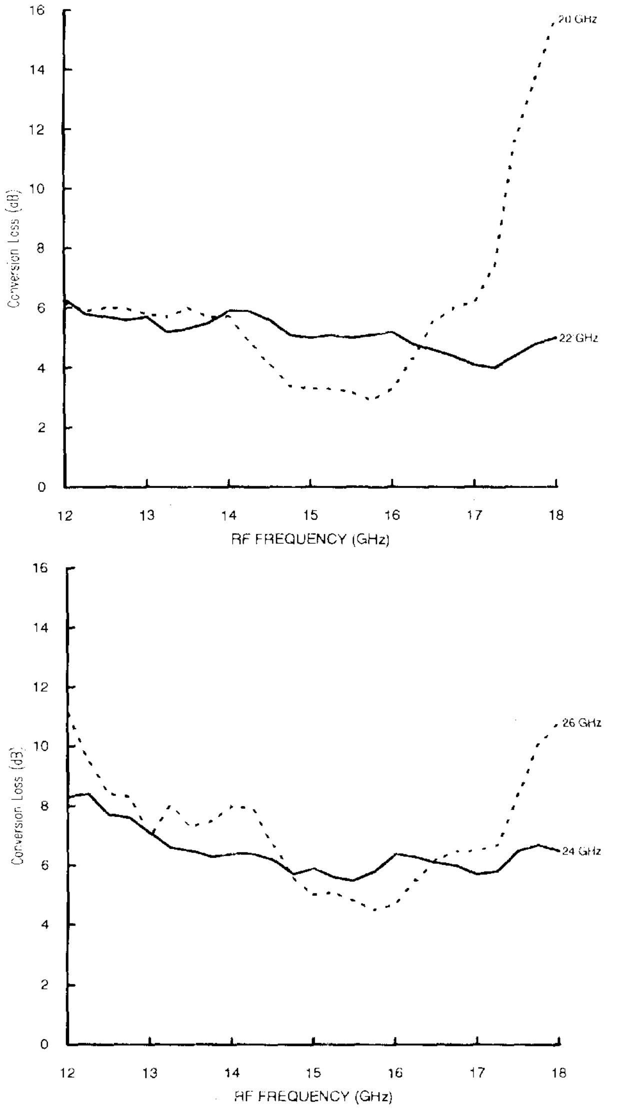

Figure 8. Mixer conversion performance for a fixed 20, 22, 24, and 26 GHz LO frequency at about +14 dBm.

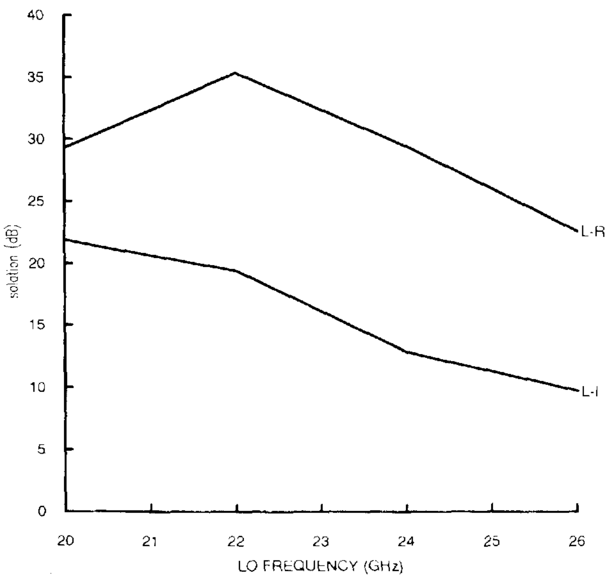

Figure 9. Measured mixer isolation between LO and RF ports and between LO and IF ports.

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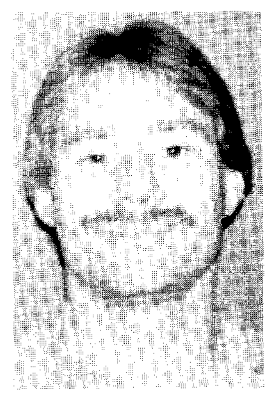
Joseph Staudinger *received a BSEE from Kansas State University and a MSEE from Arizona State University in 1980 and 1986, respectively. He has been employed by Motorola since 1981. Since 1991 he has been with the Semiconductor Products Sector in the areas of MMIC GaAs FET characterization and large signal modeling as well as circuit development of power amplifiers. Prior to 1991, he was at the Motorola Government Electronics group and directed development efforts of integrating high functionality on single MMIC die.*

Mr. Staudinger has developed numerous MMIC circuits including mixers, passive hybrids, down converters, multipliers, and amplifiers. He holds seven patents and is a senior member of the IEEE.



Mike Friesen *received a BSEE from California State University, Sacramento and the MSEE from Arizona State University in 1985 and 1990, respectively. He has been employed by Motorola Government Electronics Group since 1986, primarily focusing on 1-26 GHz MMIC design work.*

Mike is a member of the Tau Beta Pi engineering honor society.