Fully Integrated Double Balanced MMIC Mixer Using a Star Arrangement of Diodes For Extended IF Performance

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Abstract:

A double balanced diode mixer with all circuitry contained on a single MMIC die has been designed and fabricated. The mixer consists of four diodes arranged in a star configuration connected to several balun type structures. The configuration allows extracting the IF signal at a node which is a virtual ground to both LO and RF signals. Thus, compared to conventional MMIC mixers, a significant improvement in extracting the IF signal to achieve broad bandwidth performance is possible. On chip matching circuitry is included between diodes and baluns to enhance performance across a 6 GHz IF bandwidth.

I Introduction:

Frequency conversion of RF signals is commonly required in many military systems as well as commercial telecommunication applications. Many such applications demand mixer circuits which occupy smaller areas, cost less and exhibit higher levels of performance and reliability compared to MIC hybrid circuits. These constraints often dictate selecting an integrated monolithic (MMIC) rather than conventional hybrid technology as a means to implement the circuit.

To date most MMIC mixers, particularly those using diodes have been developed based on topologies typical of hybrid mixer circuits[1-3]. As such, double balanced diode MMIC mixers often consist of two baluns, Schottky diodes, and perhaps some matching circuitry to enhance performance. The baluns can be implemented using passive approaches (distributed or lumped) or by active methods. In double balanced circuits, the four Schottky diodes are usually arranged in a ring configuration.

Functionally, the two baluns establish phase/amplitude balance for the LO/RF signals and the Schottky diodes generate mixing action from their non-linearity characteristics. Thus, voltages at the LO/RF frequency are impressed with prescribed amplitude/phase characteristics across each diode via a balun. The IF signal is then extracted by one of two methods, 1) a diplexing network or 2) from the fourth port of one balun.

A key limitation of this approach, especially for wide bandwidth operation, is the efficient extraction of the IF signal component. For situations where the IF frequency is not sufficiently separated from, or extends into the RF/LO frequency range, diplexing the IF from the LO/RF signals is not possible. For this situation, the IF could be obtained via the fourth port of the LO or RF balun which has a response similar to a center tapped transformer. However, the balun frequency response must encompass that of the IF, LO which can be substantial. This results in a balun with a wide bandwith requirement (perhaps 4:1 or more) which is difficult to implement in MMIC.

The above limitation has been relaxed by developing 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 ones, it is realized completely in a planar media (MMIC). Compared to ring type mixer, extracting the IF signal is simplified for this configuration since the IF node is a virtual ground to both LO and RF signals, thus eliminating any requirements for diplexing. Although diplexing is not required, some filtering at the IF port may be possible to further 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.

II Circuit Description

The topology of the star mixer is illustrated by the block diagram shown in Figure 1. The mixer consists of three broadband baluns, an in-phase power divider network, and four Schottky diodes arranged in a star configuration. Additionally, some matching circuity is included on chip 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. The IF signal is extracted at the center of the diodes.

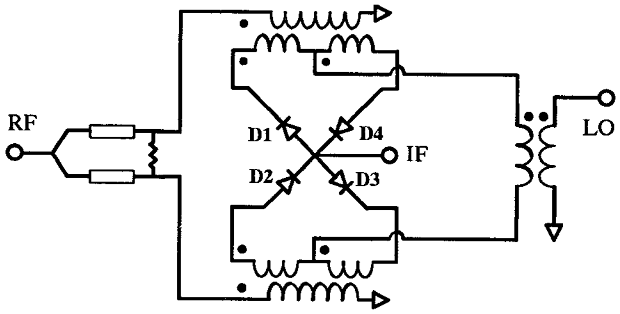


Figure 1. Schematic diagram of the MMIC diode mixer.

Functionally, the mixer translates an RF signal at 12-18 GHz with a 20-26 GHz LO signal to an IF in the range of 6-12 GHz using an LO drive level of 12 to 14 dBm. The circuit has been realized monolithically (MMIC) on a single die with dimensions of 80 mils x 100 mils x 3.5 mils.

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. Both conversion and isolation characteristics are easily examined using this method. The resulting analysis (presented below) is based on choosing the IF node (center of the diode star) as a reference (Fig. 1) for LO, RF and IF phase states.

When the RF signal is applied at the power divider port, the divider splits the signal into two equal amplitude and identical phase signals. Thus, RF signals are incident onto the two central baluns. Since the central baluns are connected to the four diodes, voltages at the RF frequency are impressed across each diode. An observation of the resultant voltages indicates two sets of diodes exhibit identical phase. (i.e., diodes D2 and D3 as well as diodes D1 and D4). Therefore, a virtual ground develops at the center of the diode star which is also the IF port.

Similarly, when the LO signal is applied at the input port of the far right balun (Fig. 1), the signal is split in amplitude and the phases are displaced (180^{o}) from each other. Hence, the LO signals incident onto the two central baluns exhibit 180 degrees of relative phase difference. Again, due to the central baluns, voltages develop across each diode. Again, two sets of diodes exhibit identical phase (i.e., diodes D1 and D2 as well as diodes D3 and D4). 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:

$$\Phi_{IF} = \Phi_{LO} - \Phi_{RF} - \Phi_{D} \quad (1).$$

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.

Table 1
Relative phase of LO, RF, and IF signals at each diode

Reference node is the IF port

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

Based on the results shown in Table 1, IF components produced in each diode exhibit similar phase and thus constructively combine at the IF port. Additionally, 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. Thus the IF signal can be extracted at this node without diplexing it from the LO or RF frequencies.

Isolation between various ports of the mixer can be determined using a a similar analysis. The isolation between the LO/RF to IF port is due entirely to signals vectorially canceling at the IF port (Table 1). Thus, 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 isolation resistor in the power divider and the fourth port of the far right balun (Fig. 1).

III Design Technique

The star mixer circuit shown in Figure 1 was realized on a single MMIC die. 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 to 26 GHz. Based on previous power divider work [4,5,8], a minimum lumped element band pass structure was chosen (Fig. 2). This passive divider easily achieves an insertion loss of about .5 dB with good return loss across octave bandwidths.

The baluns were also realized in a passive topology consisting of high/low pass filter structures similar to that reported by Parisi[9]. Additionally, matching networks were included to improve the conversion efficiency and minimize LO power requirements. To further minimize die size, much of the matching circuitry between diodes and baluns was integrated into the two central baluns.

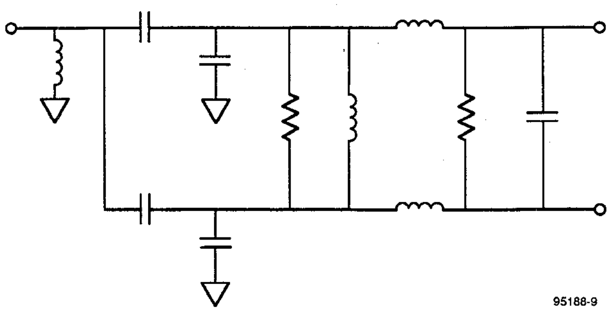


Figure 2. The power divider sub-circuit was implemented based on a minimum element topology utilizing lumped and distributed components.

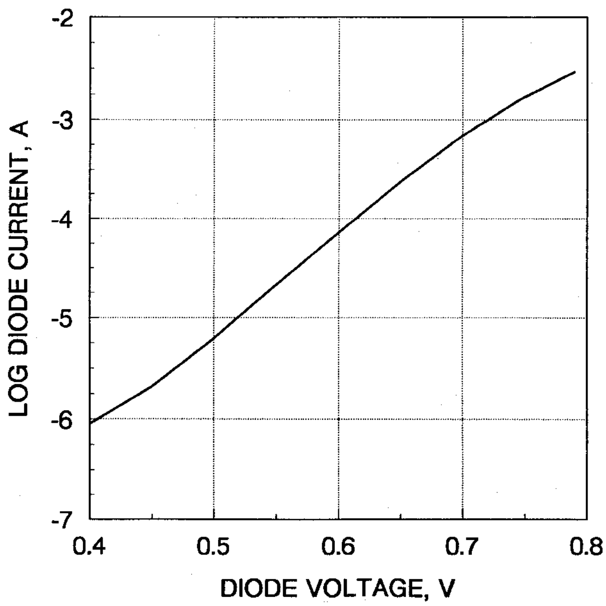


Figure 3. The current voltage characteristics of the diode were measured to determine large signal model parameters (N, I_S, and R_S). The diode exhibits a R_S of 7.0 ohms.

The design of the Schottky diodes was constrained since a standard MMIC processing method was chosen. Based on previous efforts, geometrical parameters, such as finger width, length and number were chosen to maximize the cut off frequency. Forward bias, DC, and microwave S-parameter measurements were made on diodes to determine their electrical behavior. 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.

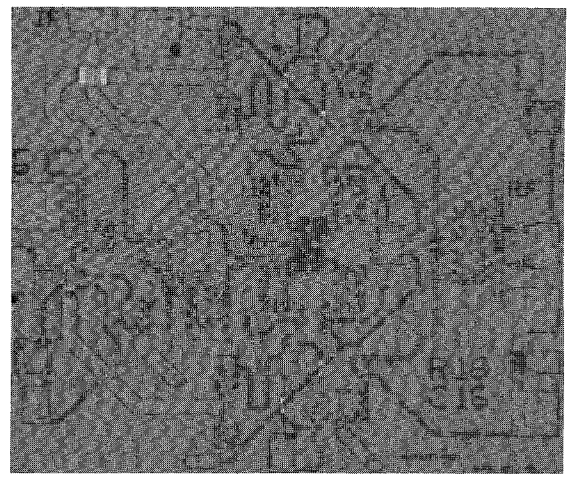


Figure 4. Photograph of complete MMIC mixer. All mixer circuitry is contained on a 80 x 100 x 3.5 mil die.

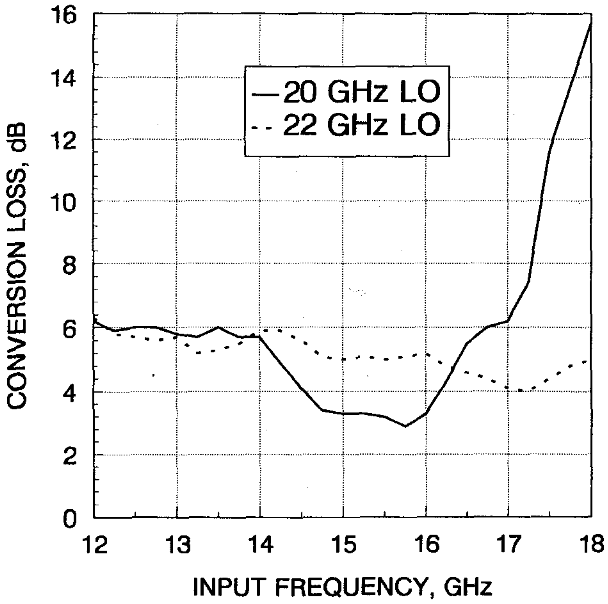
The current-voltage characteristics for the diode are shown in Figure 3. The diode exhibits a series resistance (R_S) of about 7 ohms. Similarly, capacitance-voltage measurements were made to determine diode capacitance model parameters. The results indicate 0.082 pF zero bias capacitance (C_{jo}). Hence, the diode exhibits a cutoff frequency of about 250 GHz.

Based on the large signal model of the diode, harmonic balance simulations were performed to determine impedance matching networks to enhance mixer conversion characteristics and minimize LO drive requirements. With these networks defined, the overall mixer circuit was then simulated which allowed very limited optimization due to the lengthy simulation times needed by the harmonic balance simulator.

A photograph of the completed MMIC mixer is shown in Figure 4. 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.

IV Measured Performance

Mixer performance characteristics were measured using on-wafer probe equipment. Conversion loss measurements of the mixer as a function of LO power suggests a minimum drive level of +12 dBm. This agrees well with harmonic balance circuit simulations. The measured conversion characteristics for LO frequencies of 20, 22, 24, and 26 GHz with the RF frequency swept from 12 to 18 GHz is shown in



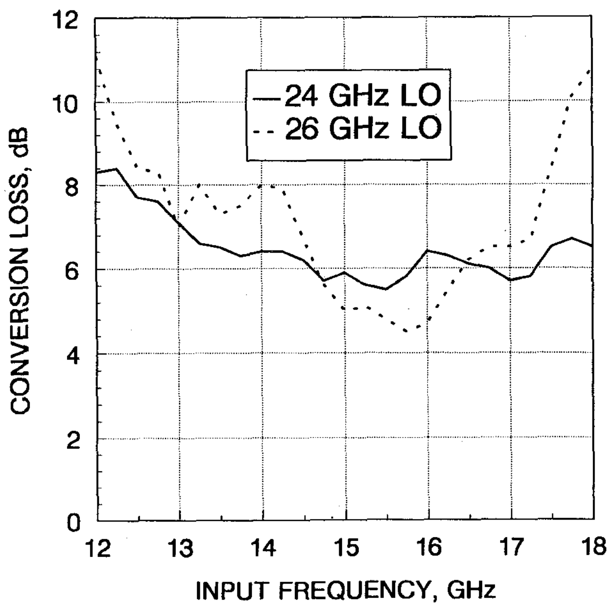


Figure 5. Mixer conversion characteristics were measured with LO frequencies of 20, 22, 24, and 26 GHz with the RF swept between 12 and 18 GHz. The local oscillator power is +14 dBm.

Figure 5. Over most of the 6 GHz IF frequency bandwidth, a conversion loss of approximately 6 dB is achieved. The isolation performance from LO to IF port was generally better than 20 dB. Isolation between LO and RF ports was approximately 30 dB.

V Summary

A complete double balanced mixer has been fabricated on a single MMIC die with excellent performance. The mixer has an RF/LO frequency bandwidth of over 100% with an IF frequency range in excess of 6-12 GHz. In this mixer, the IF signal is easily extracted without the need for diplexing.

Acknowledgements

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