# A 60 GHz Uniplanar MMIC 4X Subharmonic Mixer

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*Abstract* - **A uniplanar GaAs MMIC subharmonic mixer has been designed and fabricated using an antiparallel diode pair in finite ground coplanar (FGC) waveguide technology. This mixer is designed to operate over an RF range of 58.5-60.5 GHz, an IF range of 1.5-2.5 GHz, and an LO frequency range of 14-14.5 GHz. Of several mixer configurations tested, the best results show a maximum conversion loss of 13.2 dB over the specified frequency range with a minimum LO power of 3 dBm. The minimum upper sideband (USB) conversion loss is 11.3 dB at an RF of 58.5 GHz and an IF of 2.5 GHz. This represents excellent performance for a 4X subharmonic mixer operating at 60 GHz.**

## I. INTRODUCTION

As the demand for high-speed, high-capacity wireless data transmission becomes greater and greater, mm-wave frequencies such as 60 GHz may offer an attractive alternative to the microwave frequencies currently allocated for wireless data transmission. Although an atmospheric attenuation peak exists from 58-62 GHz due to oxygen resonance, this band could be useful for short-range links in systems such as indoor WLANs and the Intelligent Vehicle Highway System (IVHS). Downconverting a received signal from high frequencies such as 60 GHz presents a significant challenge to the RF circuit designer. For fundamental mixers, the oscillator is separated in frequency from the RF signal by some relatively small offset equal to the IF (IF=|RF-$f_{LO}$|). Mixers typically have a specified minimum LO power below which conversion loss performance degrades drastically. At mm-wave frequencies, it may be difficult to meet these power requirements with an integrated oscillator. Subharmonic mixers offer an alternative to fundamental mixers in that the LO frequency is at some integer fraction 1/*n* of the fundamental LO frequency (i.e., IF=|RF-*n* LO|). The benefit of this approach is that it allows the use of a local oscillator at a relatively low frequency at which the output power and phase noise performance may offer an advantage over that which is available at the fundamental frequency.

The most widely implemented SHM topology is the antiparallel diode configuration [1]. This consists of a pair of diodes in parallel with reversed polarity relative to one another. The advantage of this configuration is that the diode pair conducts on both the positive and negative portion of the LO cycle, resulting in an inherent *2X* multiplication of the LO frequency. Therefore, the only frequency components present in the LO switching waveform are multiples of the second LO harmonic. This suppresses the fundamental mixing response, reducing conversion loss to the subharmonic IF products.

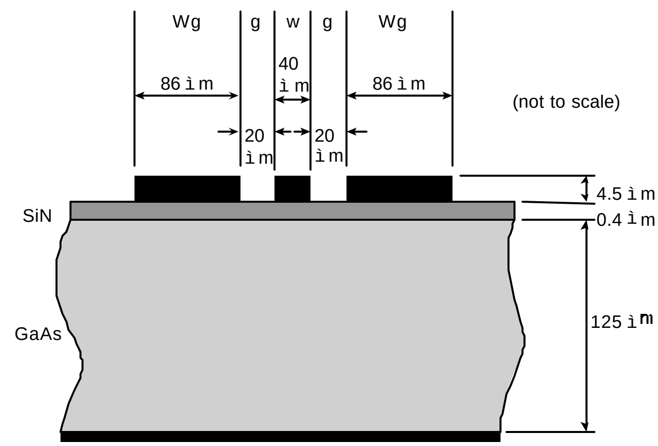


Fig. 1. Finite ground coplanar waveguide 50 Ù line dimensions

The motivation of this research is the implementation of a 60 GHz MMIC subharmonic mixer in finite ground coplanar (FGC) waveguide technology. This transmission line topology has several advantages for MMIC implementation [2], including low dispersion and line attenuation at mm-wave frequencies [3]. The coplanar ground planes obviate the need for backside ground connections, simplifying processing by eliminating the dependence on vias for ground connections as seen in microstrip.

## II. FINITE GROUND COPLANAR WAVEGUIDE DESIGN

Finite ground coplanar waveguide (Figure 1) is a coplanar waveguide (CPW) variant with truncated ground plane widths to avoid the excitation of a parallel plate waveguide mode between the CPW ground plane and backside metal plane [2], [3]. If the ground planes are made narrow enough such that the overall structure width is less than a quarter wavelength at the highest frequency of interest, excitation of the parallel plate waveguide mode may be avoided.

In canonical CPW, characteristic impedance ($Z_o$) is set by the ratio of center conductor width ($w$) to overall slot width ($w+2g$). In FGC lines, the finite ground plane width has an effect on transmission line parameters such as $Z_o$ and line attenuation (*á*). Therefore, any commonly used design tools for CPW lines such as HP LineCalc [4] are not truly accurate for FGC. In order to design FGC lines for a

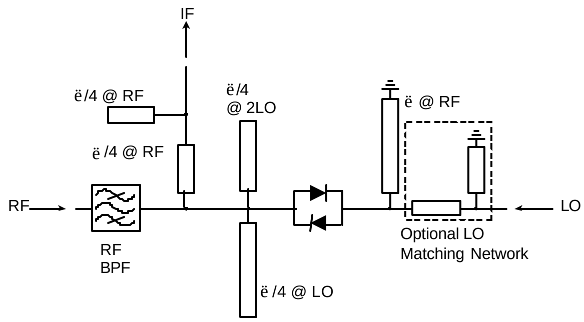


Figure 2. Schematic of 60 GHz 4X subharmonic mixer

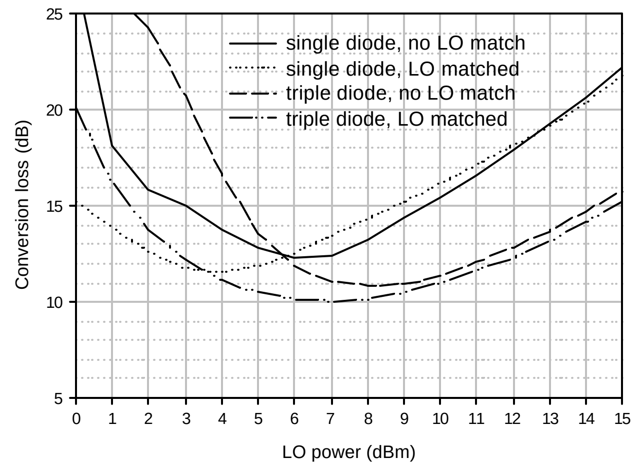


Figure 3. Simulated USB conversion loss vs. LO power for RF=60 GHz, IF=2.5 GHz

TABLE 1.
M/A-COM MSAG-5 SCHOTTKY MIXER DIODE PARAMETERS

| $I_s$ (pA) | $R_s$ (Ù) | ç | t (ps) | $C_{jo}$ (fF) | $f_{bi}$ (V) | $E_g$ (eV) | BV (V) | $I_{bv}$ (mA) |
|---|---|---|---|---|---|---|---|---|
| 0.2 | 17.6 | 1.25 | 1.0 | 13.5 | 0.73 | 1.43 | -7 | 200 |

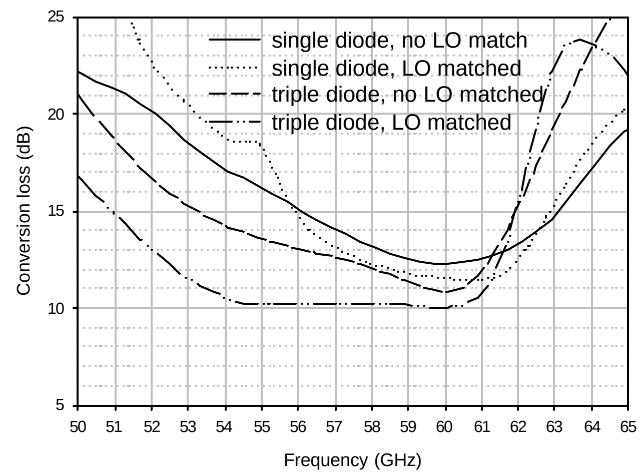


Figure 4. Simulated USB conversion loss vs. RF frequency at respective optimum LO powers, IF=2.5 GHz

specific characteristic impedance, full-wave electromagnetic simulation software can be employed for accurate prediction of á and effective dielectric constant ($å_{eff}$).

The FGC dimensions shown in Figure 1 reflect the standard 50 Ù transmission line dimensions for the given substrate as simulated in Zeland's IE3D [5]. For these dimensions, the simulated $å_{eff}$ was 7.1 and the simulated *á* was less than 2 dB/cm for all frequencies of interest.

## III. MIXER DESIGN AND SIMULATION

Mixers were designed and simulated using the Agilent EEsof Series IV simulation software [4]. The simulated mixer schematic is shown in Figure 2. These simulations were conducted with ideal distributed transmission line elements and the standard Libra p-n diode model. The diode model parameters were provided by the manufacturer and are shown in Table 1.

For best mixer performance, it is important that the full LO voltage is dropped across the diode pair. The $ë_g$/4 @ LO open-circuit stub terminates the diode pair in a short-circuit at the side opposite the LO port. Similarly, a $ë_g$ @ RF short-circuit stub on the opposite side from the RF port provides a short-circuit at RF. For a 4X subharmonic mixer, RF is approximately equal to 4 times the LO frequency. Therefore, the $ë_g$ @ RF stub is approximately equal to $ë_g$/4 at the LO frequency. This presents an open-circuit at this frequency, allowing the LO signal to pass undisturbed.

The IF port is coupled to the diodes via a $ë_g$/4 @ RF transmission line. On the IF port side of the transmission line is a shunt $ë_g$/4 @ RF open-circuit stub. The purpose of this network is to present an open-circuit to the RF signal so that the IF port does not degrade conversion loss by loading the RF signal. The components used in this network are electrically small enough at IF to be essentially transparent at that frequency. The RF bandpass filter (BPF) indicated in the schematic serves a similar purpose. This filter passes the RF frequencies, but presents an open-circuit at IF frequencies so the IF signal is not loaded by the impedance of the RF port. This filter was implemented with an FGC series open-circuit stub, which was modeled with an equivalent lumped L-C circuit based on IE3D modeling for Libra simulations.

Since this is a 4X subharmonic mixer, it is desirable to suppress the 2X subharmonic conversion product at RF-2$f_{LO}$. This product represents a loss mechanism to the 4X subharmonic conversion product by stealing converted RF power that would otherwise be converted to the 4X subharmonic IF. Since the RF is approximately equal to 4$f_{LO}$, the RF-2$f_{LO}$ product falls at approximately 2$f_{LO}$. Therefore, the $ë_g$/4 @ 2$f_{LO}$ stub is included at the side of the diode pair from which the IF is extracted. Finally, an optional LO matching network was included in an effort to reduce the LO power required for optimal mixer conversion loss. This network consists of a series delay line followed by a shunt short-circuit stub. The lengths of these stubs were iteratively tuned to provide good conversion loss at a relatively low LO drive level. It was observed that the best

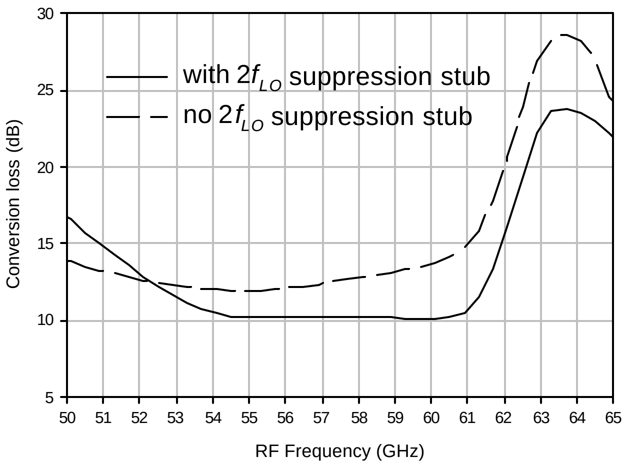


Figure 5. Simulated USB conversion loss vs. frequency with and without 2 $f_{LO}$ suppression stub, IF=2.5 GHz, optimum LO power

conversion loss does not necessarily correspond to the best 50 Ù match, so the final matching networks represent a compromise between a good conjugate match and optimal conversion loss.

The diode pair indicated in the schematic was implemented in two variant Schottky diode configurations. In the first configuration, the diode pair is connected as shown in the schematic. In the second variant, however, three parallel Schottky diodes are substituted for each diode indicated in the schematic. This is an effort to reduce the effects of diode series resistance ($R_s$) on mixer conversion loss. $R_s$ is known to be a major mechanism in diode mixer conversion loss, and the parallel combination of three diodes divides the effective $R_s$ of the structure by an approximate factor of three.

The simulated data for the four mixer variations are shown in Figures 3 and 4. The effect of the matching networks can be seen in Figure 3. In the case of the single diode mixer, the optimum LO drive level shifts from between 6 and 7 dBm to between 3 and 4 dBm with the addition of the LO matching networks. A similar shift is shown for the triple diode mixer, for which the optimum LO power shifts from 7-9 dBm to 6-8 dBm. In both cases, the LO matching networks result in a slight improvement in conversion loss. The best simulated conversion loss shown by all variants is 10.0 dBm for the triple diode mixer with LO matching at an RF of 60 GHz with an LO power of 7 dBm at 14.375 GHz.

The utility of the $2f_{LO}$ suppression stub can be seen in Figure 5. From this graph, it is evident that without this stub, RF power conversion to other subharmonic products (e.g. RF-$2f_{LO}$, $6f_{LO}$-RF) degrades the conversion loss by 2-4 dB across the band 55-60 GHz.

## IV. Fabrication and Measurement

The mixer circuits designed in the previous section were implemented on a 125 ìm GaAs substrate in the M/A-COM MSAG 5 process. The tuning stubs were fabricated as individual test circuits to verify resonance at the desired frequencies. All stubs were found to resonate approximately 7% above their intended resonant frequency.

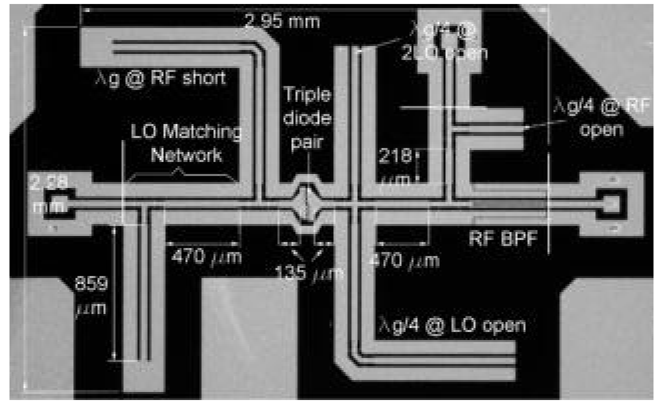


Figure 6. Photograph of triple diode mixer with LO matching

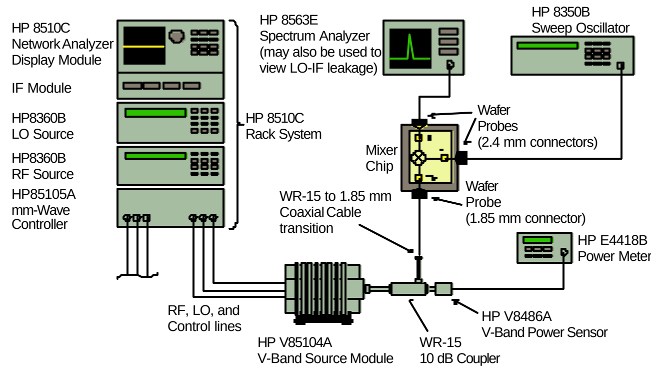


Figure 7. Mixer conversion loss test setup

These stub measurements suggest that if the optimum mixer operating frequency is determined solely by the resonant frequency of the stubs, the mixers should be tuned to a 64 GHz RF frequency. An I-V measurement was made for the fabricated Schottky diodes in order to extract an approximate value for $R_s$. The extracted value was 20.0 Ù, compared to the manufacturer's specification of 17.6 Ù. This could account for a lower measured conversion loss than the simulated value.

A photograph of the fabricated triple diode mixer with LO matching is shown in Figure 6. Wafer probe pads are located at the respective reference planes of the IF, RF, and LO ports for measurement purposes. The overall area for the largest mixer layout (triple diode mixer with LO matching) excluding the probe pads is approximately 2.3 mm x 3.0 mm. The test setup for conversion loss is shown in Figure 7. This setup may be easily modified for LO-RF and LO-IF isolation measurements by using the spectrum analyzer to monitor LO power at the RF and IF ports. The losses of all cables, probes, etc. were calibrated out up to the reference planes indicated on the layout photograph.

The measured USB conversion loss vs. RF frequency is shown for the various mixer configurations in Figure 8. The simulated data suggest that the mixers display optimal conversion loss at the frequency to which the stub elements are tuned. If this holds true for the actual fabricated mixers, the measured optimal conversion loss should occur at an RF of 64 GHz. Figure 8 shows that this is not the case; the single diode mixers are optimally tuned between 60.5 and

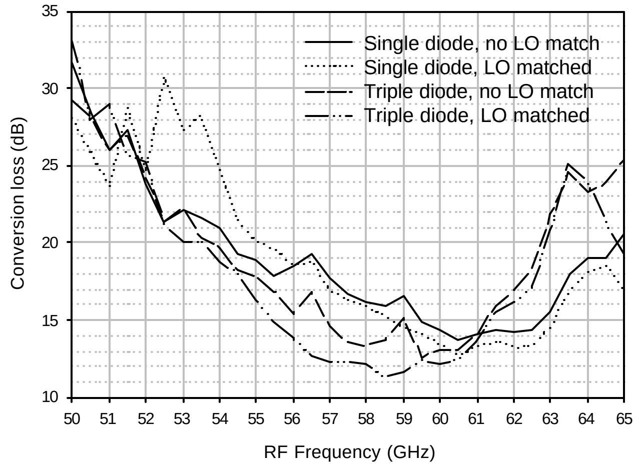


Figure 8. Measured mixer USB conversion loss vs. RF frequency, IF=2.5 GHz, optimum LO drive level

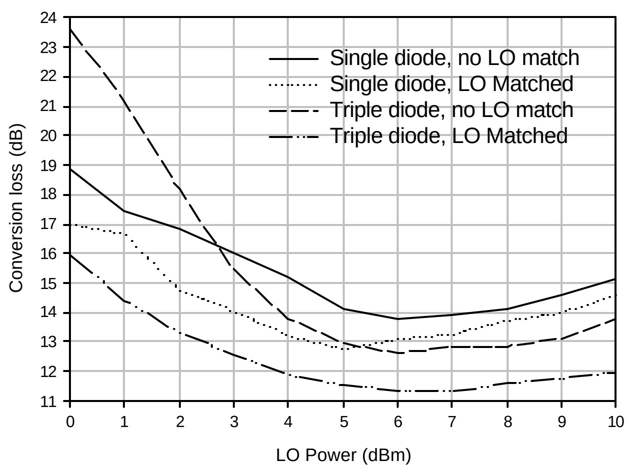


Figure 9. Measured mixer USB conversion loss vs. LO power, RF=60 GHz, IF=2.5 GHz

62.5 GHz and the triple diode mixer are tuned between 58.5 and 60.5 GHz. It is believed that this is due to parasitic capacitance in parallel with the diodes in the mixer layout causing an in-band loss increase over the band. This capacitance data was not available for diode modeling in Libra. Its effect is more pronounced in the case of the triple diode mixer because the layout must be physically wider due to the three adjacent diodes, resulting in increased parasitic capacitance. This explains why the increase in conversion loss is more drastic for the triple diode mixers and begins to take effect at a lower frequency. An LO power sweep is shown in Figure 9. The benefit of the LO matching network is demonstrated in an improvement in conversion loss and a reduction in required LO power. For the case of the triple diode mixer, the additional matching network allows the mixer to operate with better than 13 dB conversion loss at LO powers as low as 2.5 dBm

Isolation measurements were made for the LO-IF and LO-RF signal paths. For the mixer variant with the best conversion loss, the triple diode mixer with LO matching, the LO-IF isolation is as low as 17 dB. This is due to the fact that the stubs are mistuned to an RF of 64 GHz, corresponding to an LO of 15.5 GHz. LO isolation at all ports is largely determined by the rejection provided by the $\ddot{e}_g/4$ @ LO open-circuit stub. The worst-case LO-IF isolation occurs at an RF of 58.5 GHz (LO=14 GHz for USB mixing at IF=2.5 GHz), well outside the optimum rejection provided by this stub. The LO-RF isolation, which is also dominated by the rejection of the $\ddot{e}_g/4$ @ LO open-circuit stub, is 33 dB worst-case for the intended frequencies of operation. Both LO-IF and LO-RF isolation would be improved by retuning the resonant stubs for the correct operating frequencies in a subsequent revision.

## V. CONCLUSIONS

A high-performance 60 GHz mixer has been fabricated in a uniplanar FGC MMIC technology. The size of the circuit is approximately 2.3 mm x 3 mm excluding wafer probe pads. The best performance is displayed by the triple diode mixer with an LO matching network. This circuit displayed an 11.3 dB USB conversion loss at an RF of 58.5 GHz, and IF of 2.5 GHz. The USB operating range for the RF has been defined as 58.5-60.5 GHz and the IF range has been defined as 1.5-2.5 GHz. Less than 13.3 dB conversion loss is achieved over this range with an LO power of 3-10 dBm.

Two other recently reported 60 GHz antiparallel diode 2X subharmonic mixers have shown conversion losses of 12 dB [6] and 13 dB [7]. Typically, a 3-dB conversion loss degradation is observed between 2X and 4X subharmonic mixers. With these reported results as a benchmark, a conversion loss under 13.3 dB over the defined range of operating frequencies represents excellent conversion loss for a 4X subharmonic mixer.

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