HIGH QUALITY X-BAND MONOLITHIC DIODE MIXER

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ABSTRACT

A mixer analysis program has been used to design a single balanced MMIC diode mixer. The predicted conversion loss is better than 6 dB over 2 GHz B.W. at X-band and the input VSWR is better than 2:1. An inter-mesa airbridge technique has been developed to provide low parasitic connections to the diode. Also 0.6 dB insertion loss Lange couplers have been demonstrated and via holes have been successfully etched through 200 μ of GaAs.

INTRODUCTION

This paper describes the design, fabrication and performance of an MMIC single balanced diode mixer. It is believed that this is the first report of an attempt to design a diode mixer in a rigorous manner. FET mixers were not considered because of their higher 1/f noise at conventional intermediate frequencies.

Traditionally mixers have been developed in an almost entirely empirical manner partly because this is much simpler than attempting a theoretical design and partly because of the poor correlation commonly observed between mixer theory and experimental results. This is thought to be caused by the large and uncertain parasitics close to the diodes, which upset the important harmonic termination conditions.

An empirical approach is not viable for monolithic mixers because (a) post fabrication adjustment is not possible and (b) each cycle of design, fabrication and evaluation is slow and expensive. MMICs, however, have the advantage that the parasitics associated with the active devices are much smaller, more readily quantified and better controlled. The mixer matching networks were therefore designed using a sophisticated mixer analysis program.

MIXER DESIGN

Circuit Configuration

The target specification called for less than 6 dB conversion loss over the RF band 9-11 GHz and the IF band DC -500 MHz, combined with good input matches and 20 dB of Local Oscillator (LO) to signal isolation. Furthermore it was required that the circuit must operate with between 5 and 12.5 mW of LO input power and no DC bias. Three combining techniques are available to provide the required isolation: combining with FETs feeding a single diode, passive combining with a hybrid feeding a pair of diodes (a single balanced mixer) and a pair of baluns feeding a ring of diodes. It is considered that it will not be practical to design baluns for use in single sided structures on high dielectric materials. FET combiners are not without their advantages, but they are likely to lead to a degraded noise performance unless used with preamplification.

Single balanced mixers require a 180° 3 dB coupler which unfortunately is inconveniently large for use in monolithic circuits, but the Lange coupler, which is inherently a 90° coupler, is small enough to be usable. Over a moderate bandwidth it can be stretched to behave like a 180° coupler by adding a quarter wavelength transmission line to one of its output ports. Clearly the phase shift across this transmission line is frequency sensitive but over the limited bandwidth under consideration it is calculated that this will be acceptable.

In order to meet the input match and conversion loss specifications it is necessary to interpose matching networks between the diodes and the coupler. In the fundament al band, each of these networks is required to provide matching, but the impedance which they present to the diodes at the harmonics has a significant effect on the overall circuit performance. Both the conversion loss and the effective diode impedance at LO and signal level are affected.

Because of this complexity it seemed that the best way to find a good matching circuit was to consider several possible topologies over a wide range of circuit values and diode parameters, treating each computed result as an experimental result and seeking to find the optimum. The only constraints in this process are physical realisability and computer time. In a similar way a range of IF output circuits were considered.

Lange Coupler

The initial design of this component which was undertaken using Super Compact, showed that it is possible to improve the coupler's insertion loss if a slightly lower isolation can be accepted.

In conventional hybrid technology the lines of the Lange coupler are connected using bondwires, which introduce primarily inductive parasitics, but this approach is not feasible for monolithic couplers. However, both airbridge and dielectric bridge interconnections are possible. These provide a low inductance interconnection but with a parasitic capacitance to the line being bridged. These capacitances tend to equalise the even and odd mode phase velocities in the coupler which should improve its bandwidth but it seems that they can lead to somewhat reduced isolation. Furthermore they slightly reduce the length of the coupler required for a given centre frequency of operation, which marginally decreases the coupler's insertion loss and saves chip area. The measured performance of these couplers is 3.7 ± 0.5 dB over the band 7-11.3 GHz, with an insertion loss of only 0.6 dB up to 10 GHz. It is expected that the insertion loss will be further reduced by increasing the metallisation thickness from the present 0.8 μm.

The Diode

In order to be able to achieve a high performance mixer it is necessary first to produce a high quality diode. The practical measure of diode quality is its cut off frequency which is defined as $1/2\pi C_0 R$, where C_0 is the zero bias capacitance and R is the series resistance measured in forward conduction. The capacitance depends primarily on the area of the Schottky contact and the doping of the active layer. A low doping-level leads to a low capacitance, but also to a high resistance. It has been found in discrete devices that a 10^{17} doped active layer 0.1-0.2 μm thick on an n^+ substrate is a good compromise. Unfortunately an n^+ substrate would short out the passive circuitry on an MMIC, and it is necesary to use a local n^+ layer. Currently this is being achieved by growing an n/n^+ epilayer on semi-insulating GaAs and etching it away where it is not required.

In order to reduce the resistance for a given capacitance it is attractive to use diodes with a finger geometry, similar to a FET with source and drain connected, because this increases the periphery for a given area. The effects of the finger-width, n^+ layer thickness and contact resistance were investigated by modelling the structure on resistive paper, from which it was concluded that for a 0.09 pF diode the optimum finger width is around 2 μm and that there is little to be gained from using more than two diode fingers or from using more than 1 μm of n^+ material. Clearly it is essential that where the Schottky finger leaves the diode mesa it neither shorts to the n^+ layer nor has a large parasitic capacitance. These dangers have been avoided by developing an inter-mesa airbridge technology.

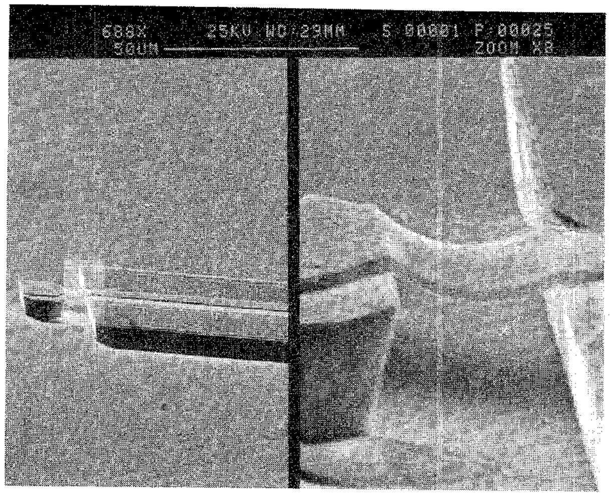

Figure 1 : Inter-mesa airbridge

Via Hole

Early in the design it became apparent that it would be necessary to provide a low impedance RF path to ground at the IF output. Realising this with a via hole not only improves the performance but also reduces the variability and assembly cost inherent in the use of multiple bond wires. Figure 2 shows via holes etched through 200 μm of GaAs

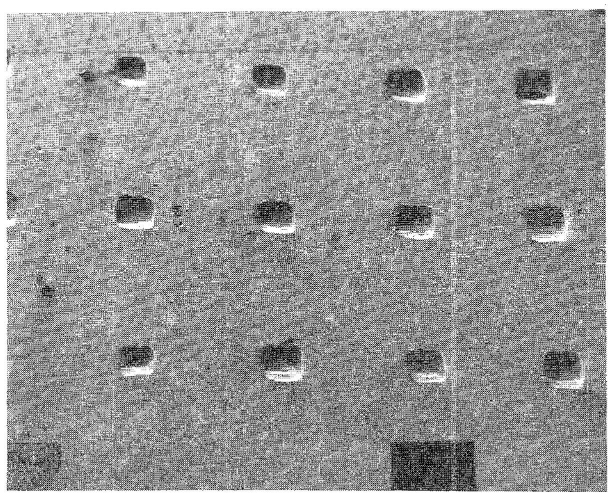

Figure 2 : Via holes in 200 μm GaAs

using a standard etch under extreme agitation. Initial hole dimensions of 140 μm and 160 μm have been used.

Computational Approach to Mixer Design

It is possible to reduce the computational work required to analyse the balanced mixer, by using its symmetry to reduce it to an equivalent single ended mixer.

During the 1970s several computer programs were written to analyse single ended mixers, of which perhaps the best is that of Siegel and Kerr (1-2). This program separates the diode from the matching network analysing the former in the time domain and the latter in the frequency domain, making it both accurate and computationally efficient. It implicitly assumes however that the embedding circuit is lossless at the Local Oscillator (LO), signal and IF frequencies. Furthermore it is written as an analysis program which means that the data entry is clumsy and the output data is voluminous.

The program has been modified to include circuit losses and simplified by the omission of certain unwanted features. Over the range -1 to +0.7 V a normal inverse square root capacitance law is assumed, but outside this range the capacitance is assumed constant. The most extensive changes however have been concerned with converting from an analysis to a design approach. Circuits can be entered in either lumped or distributed form and any combination of circuit or diode parameters may be scanned over a range of values. From these the embedding impedance at fundamental and the first seven harmonics are calculated making allowance for frequency dependent losses. The program calculates conversion losses and VSWRs and generates extensive summary tables to facilitate the identification of global optima.

Circuits Investigated

Initially a lumped element matching network was considered but even though promising performance was being predicted it was decided that it would be simpler and better to use transmission lines as the matching elements. Two circuits were analysed which included open and short circuit elements for matching. Both showed that open circuit stubs tend to reduce the bandwidth. Using a short circuit stub adjacent to the diode a good compact design was found, but when the likely effects of the mismatch of the Lange coupler at the second harmonic were included the performance became unstable, demonstrating parametric effects. It was thus decided that the design must include a shorted quarter wavelength line to i solate the impedance seen by the diode from the Lange coupler at the second harmonic.

Two further matching circuits were cons idered over a range of values which showed that a π-network with the shorted quarter wavelength line adjacent to the diode gives good predicted performance. It seems that the shorted quarter wavelength adjacent to the diode has two beneficial effects. It significantly reduces the real part of the effective diode impedance seen by the LO and also at high drive levels over a narrow band in frequency it leads to a large reduction of the effective capacitance of the diode. Higher impedance lines tend to be better for matching, but lead to higher resistive losses. It seems that 80 Ω lines provide a good compromise between these two effects. Furthermore it seems that the optimum diode size capacitance is around 0.09 pF.

The IF circuit is required to look like an open circuit over the IF band and a short circuit at all RF frequencies. It was found that this requirement can be met by a single capacitor to ground for the IF band under consideration.

Circuit Layout and Predicted Performance

Figure 3 shows the layout of the circuit and Figure 4 the predicted performance for a 1 MHz IF

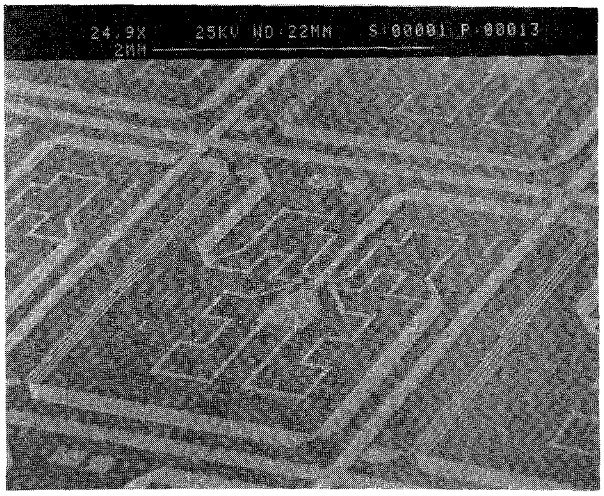

Figure 3 : Mixer circuit layout

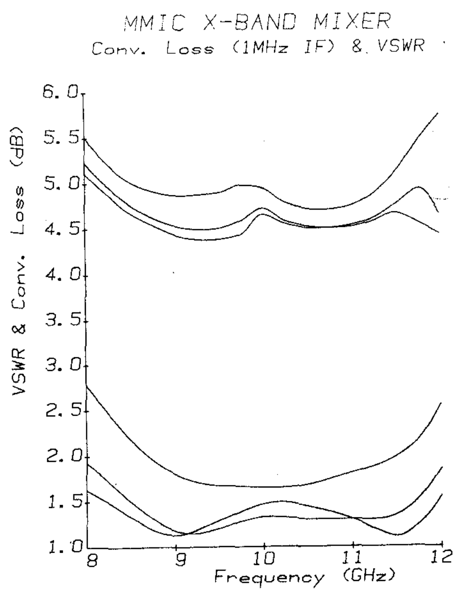

Figure 4 : Predicted performance at three drive levels

at 3 drive levels (2, 3.5, 5 mA rectified current in each diode). It can be seen that the overall predicted conversion loss at 1 MHz IF is better than 5 dB in the band 9-11 GHz. This figure rises to 5.4 dB for 500 MHz IF, not including the Lange coupler losses. Also the LO input VSWR is better than 1.9:1 in the band (better than 1.4:1 at 3.5 mA rectified current) and the LO power requirement is slightly less than 1 mW/mA at all three drive levels. It has been observed that the main effect of varying diode series resistance is on the conversion loss, which changes at the rate of some 0.1 dB/Ω. For the case of 2 mA rectified current at 10 GHz with a 1 MHz IF it has been possible to account for the overall conversion loss of 4.95 dB as follows:

3.01 dB	'Basic' conversion loss
0.27 dB	Input mismatch
0.51 dB	Output mismatch
0.40 dB	Diode series resistance
0.38 dB	Circuit losses at signal frequency
0.05 dB	Circuit losses at IF
+ 0.33 dB	Other losses e.g. harmonic terminations
4.95 dB	Predicted conversion loss

CONCLUSIONS

A single balanced monolithic diode mixer has been designed in a rigorous manner to give satisfactory performance over 2 GHz at X-band. An inter-mesa briding technology has been established to provide low parasitic connections to 'finger' diodes, 0.6 dB insertion loss Lange couplers have been demonstrated and via holes have beeen successfully etched through 200 μm GaAs.

ACKNOWLEDGEMENT

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