# Low Cost Millimeter Wave Monolithic Receivers*

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## Abstract

A 35 GHz receiver using GaAs monolithic and hybrid circuits has been developed for low cost manufacture. The receiver is comprised of a downconverter, an If amplifier and voltage regulators. This paper will report on the design, fabrication, integration, packaging and testing of a monolithic mixer, a monolithic Gunn Diode Oscillator and a GaAs Downconverter circuit which has exhibited a SSB receiver noise figure of 9.5dB

## Introduction

There are many system applications requiring small size, light weight and low cost millimeter-wave receivers such as the one shown schematically in figure 1. Typical applications call for unit-cost in the hundreds of dollars, yearly volumes on the order of 50,000 units and availability within five years. At the present time it is extremely difficult to meet these objectives with either hybrid or monolithic circuit technology. The present paper addresses the manufacturing problem described above using monolithic circuit technology.

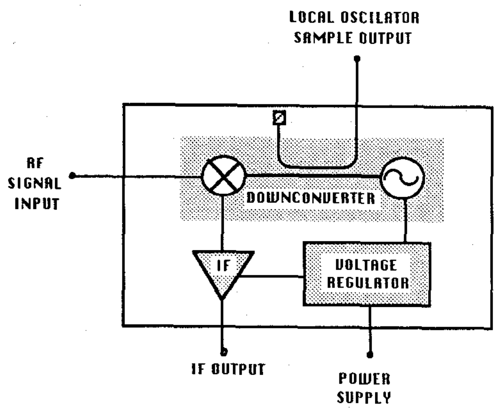


**Figure 1 - Block Diagram of Millimeter Wave Receiver**

Components in the receiver are the downconverter, IF amplifier and the voltage regulator. The highest cost component in the receiver is the downconverter. We will address the fabrication of the downconverter since this will provide the greatest cost reduction.

From a technology viewpoint the integration of the downconverter presents the greatest challenge. For example, Monolithic mixers have been demonstrated in many laboratories, but the transfer of technology to manufacturing has not yet taken place. Monolithic Gunn diode oscillators are being developed in several laboratories. However, their output powers are still significantly lower than those of hybrid units. Furthermore, the integration of planar mixer and Gunn diodes has not yet been demonstrated. These issues will be addressed in the discussions on monolithic mixers, planar Gunn diode oscillators, GaAs downconverters and receivers.

## Monolithic Mixer

The photograph of the monolithic balanced mixer shown in figure 2. The dimensions of the die are 2.5mm by 2.5mm and the substrate thickness is 100 micrometers. A 50-Ohm microstrip rat-race coupler is used as a diplexer to combine the input and the local oscillator signals. The output arms of the coupler are connected to two planar Schottky barrier diodes where mixing products are generated. A radial line stub is used to suppress higher order harmonics. The scanning electron micrograph of a planar Schottky barrier diode is shown in figure 3. The active area of the anode is circular with a nominal diameter of 2.5 μm. The active layer for the diode is a 0.3μm thick N-type layer which is doped to a concentration of $1\times10^{17}cm^{-3}$. The N layer is grown over a 3.5μm $N^+$ layer doped to a concentration of $2\times10^{18}cm^{-3}$. These layers are grown sequentially in a MOCVD reactor. The fabrication sequence follows proceedures which have been reported previously(3). Device isolation was accomplished by mesa etching. The present monolithic mixers were fabricated by production personnel. Because this process sequence is akin to that of mature products, we expect to proceed

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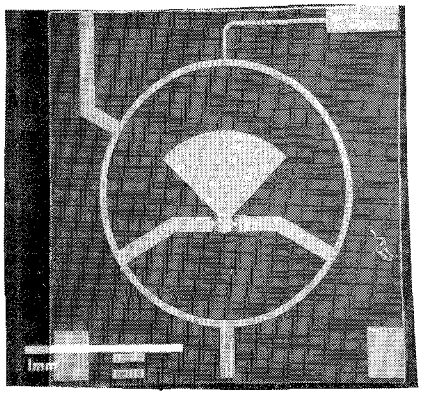

**Figure 2 - Ka Band Monolithic Balanced Mixer**

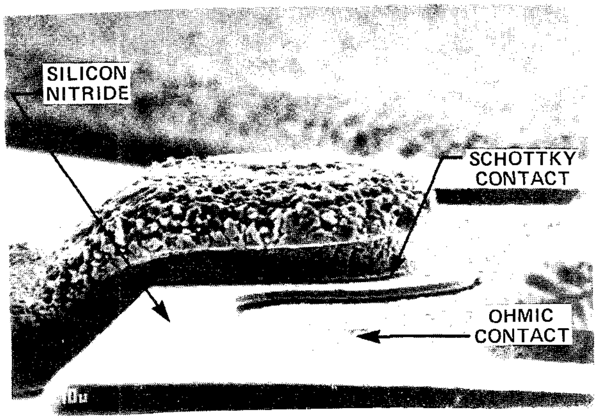


Figure 3 - SEM Micrograph of Schottky Barrier Diode

faster on the learning curve. Projected unit cost in the tens of dollars seem realistic even at moderate production volumes.

Monolithic mixers were mounted in fixtures with coaxial connectors for RF evaluation. The input VSWR into the mixer was below 1.7:1 from 34 to 35 GHz. Isolation between RF and LO ports is greater than 27dB. Noise figures exhibited by monolithic mixers from three different wafers are shown in figure 4. This data includes the noise contribution of 1.3 dB for the IF amplifier, connector losses and transmission losses from connecting lines in the fixture. For intermediate frequencies in the range of 50 to 700 MHz noise figures are in the range of 4 to 5 dB for mixers with closely matched ideality factors. The higher noise figure of unit OM-1277-4 has been correlated to differences in the ideality factors. shown in figure 4

The monolithic mixer exhibited state-of-the-art DSB noise figure of 4.2dB. This noise figure extends the data base on monolithic mixers (ref.1) and establishes the performance competitiveness of monolithic mixers fabricated in a manufacturing facility by production personnel.

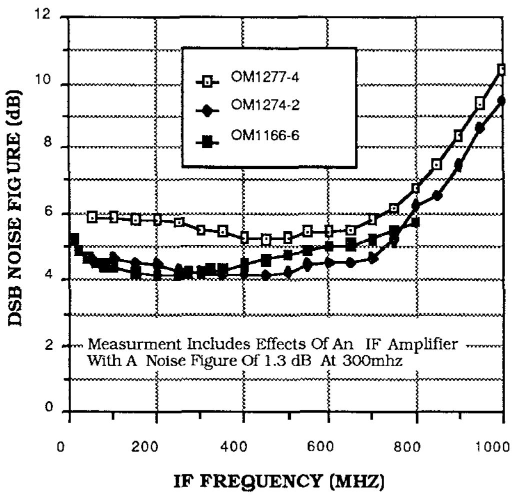


Figure 4 - Noise Performance of Monolithic Balanced Mixer

## Monolithic Gunn Diode Oscillator

Monolithic oscillators integrating planar Gunn diodes and coplanar waveguide resonators were first reported by Wang et.al.(2). In the present oscillator , a microstrip implementation was chosen because of ease of integration with the balanced mixer. The photograph of the monolithic Gunn diode oscillator is shown in figure 5. The design is based on a 20Ω half-wave-length resonator driven by a planar Gunn diode. Energy stored in the resonator is extracted by an edge-coupled quarter-wave section with even and odd mode impedances of 22.5 and 17.5 ohm, respectively.

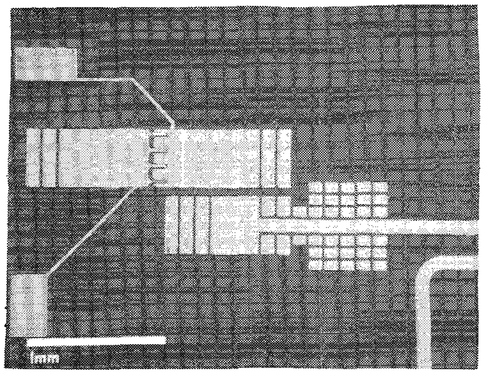

**Figure 5 - SEM Micrograph of Monolithic Gunn Diode Oscillator**

Tuning pads were provided on the mask set to investigate the ability to modify output match and oscillation frequency. Experiments indicate sensitivity of the output frequency to the dimensions of the resonator is approximately 17

MHz/μm. For process tolerances of 2 μm, the corresponding frequency variations will be on the order of 70 MHz. The effects of tuning pads on the output line of the oscillator proved to be negligible. Consequently tuning pads will be eliminated.

To reduce power density and parasitic series resistance, the active area of the diode was divided into four individual sections with unit areas of 10 μm by 90 μm, separated by 100μm. A SEM micrograph of a unit section is shown in figure 6. Anode and cathode contacts form an interdigitated pattern located at the center of the resonator. Infrared temperature scans of the active areas showed a temperature rise from 52ºC to 71ºC, corresponding to a thermal impedance in the range from 145 to 202 ºC/W

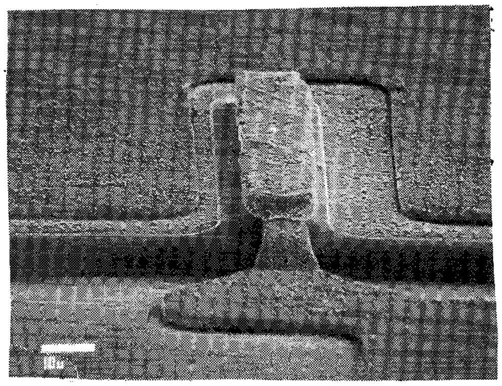

**Figure 6 - SEM Micrograph of a Unit Section of the Gunn Diode**

A cross-sectional diagram of the planar Gunn diode is illustrated in figure 7 The Gunn effect takes place in the 3μm $N^-$ layer, which is doped to a concentration of 2.2 $10^{15}cm^{-3}$. This layer is located between two N+ layers each one doped to $2x10^{18}cm^{-3}$. The thickness of the upper and lower N+ layers are 0.5μm and 3.5μm, respectively. The epitaxial layers are grown sequentially in a VPE reactor. Major operations in the process sequence of the planar Gunn diodes are: fabrication of the upper ohmic contact, definition of the active area of the diode by chemical etching of the $N^-$ layer, fabrication of the lower ohmic contact and device isolation by mesa etching.

RF evaluation results from the monolithic oscillators are shown in table I.

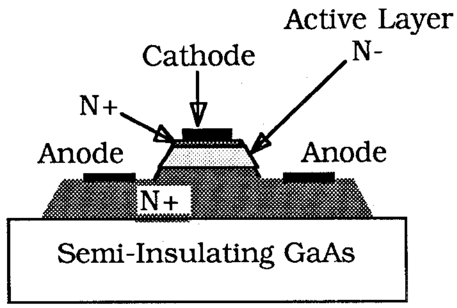


**Figure 7 - Cross-Sectional Diagram of the Planar Gunn Diode**

| Parameter | Monolithic Series Oscilator | | GaAs Circuit Shunt Oscillator (Discrete Gunn Diode) | |
|---|---|---|---|---|
| | Unit 1 | Unit 2 | Unit 3 | Unit 4 |
| Frequency of Oscillation | 35.85GHZ | 36.9GHz | 34.1GHz | 34.75GHz |
| Frequency Drift (1 to 31 Sec. after Turn on) | -0.9MHz | +1.1MHz | -6.5MHz | -3.1MHz |
| ΔFreq./ΔTemp. | -3.75MHz/C | -5.25MHz/C | -1.75MHZ/C | -2.25MHz/C |
| Frequency Pushing | -282MHz/V | -578MHz/V | +58MHZ/V | +40MHZ/V |
| Frequency Pulling (1.2 : 1 VSWR | 14.5MHZ | 21.3MHZ | 20.9MHz | 20.7MHz |
| Output Power | 2.3dBm | 0dBm | 20.2dBm | 19.3dBm |
| Operating Voltage | 4.3V | 5.1V | 4.1V | 4.5V |
| Operating Current | 95mA | 85mA | 931mA | 598mA |

**Table 1 - RF Performance of Oscillators**

Parameters in the table are relevant to system designers. These results extend the available data base on monolithic oscillators. The output power of 2.3 dBm is comparable to the 1.9 dBm reported by Wang and co-workers for a diode area of 10μm by 80μm (2). Examination of bias currents indicated that only one of the four active areas of the Gunn diode was operational. Further work to correct problems and increase the output power of the oscillator to the 10 to 15 dBm range is underway.

For purposes of comparison, hybrid oscillators using discrete Gunn diodes were also fabricated. The circuits in these oscillator were fabricated on GaAs substrates. In this case the resonator is driven in shunt by a discrete Gunn diode. Frequency drift of the hybrid oscillator is higher at turn-on because more power is dissipated by the discrete Gunn diodes. For the same reason the frequency dependence on case temperature is lower. Frequency pulling is comparable in both kinds of oscillators. The output power exhibited by hybrid oscillators using GaAs circuits were in the range of 80 to 100mW . The higher power is due to higher current Gunn diodes.

## MONOLITHIC DOWNCONVERTERS

The objective is to develop a fully monolithic downconverter. A photograph of a monolithic downconverter circuit is shown in figure 8. This design integrates balanced mixer, local oscillator and RF coupler. This mask set was used to demonstrate selective epitaxy and the fabrication process. At the present time, the output power of the local oscillator is insufficient for driving the mixer in the downconverter. Progress in monolithic oscillator development will be incorporated in the downconverter.

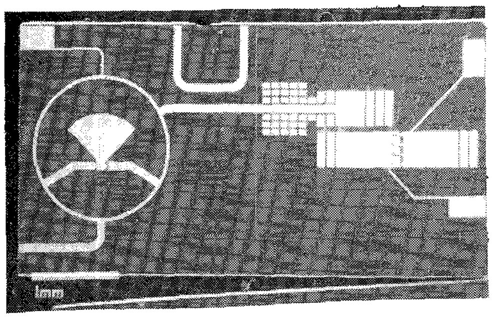

**Figure 8 - SEM micrograph of Monolithic Downconverter**

Concurrently an interim downconverter with a lower level of integration was also implemented. This version integrates the balanced mixer, coupler and the passive circuit for the local oscillator. A photograph of the interim GaAs downconverter circuit is shown in figure 9. The fabrication cost of the interim downconverter is directly proportional to the cost of monolithic mixers multiplied by the ratio of their areas. Therefore projected cost in the tens of dollars appear to be quite possible.

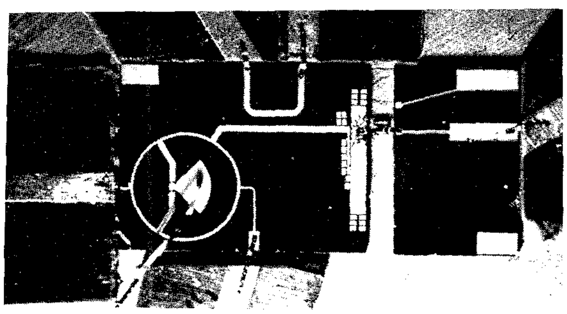

**Figure 9 - Photograph of Interim GaAs Downconverter Circuit**

## MILLIMETER-WAVE RECEIVER

A photograph of the Ka-band receiver is shown in figure 10. The interim downconverter circuit is located in the lower portion of the package. The GaAs circuit is mounted on a carrier fabricated using a copper tungsten material that matches the thermal expansion coefficient of GaAs.

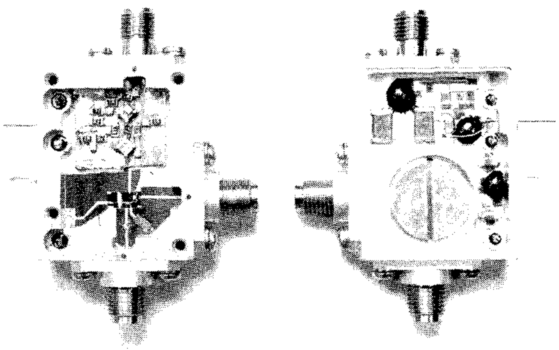

**Figure 10 - Photograph of Ka Band Receiver**

The bipolar IF amplifier and voltage regulator are placed in the upper-front and back side of the package, respectively. Selection of the IF amplifier was based on noise performance. Current GaAs and Silicon monolithic amplifiers provide noise figures in the range of 2-2.5dB from 200 to 700MHz. In this range Si bipolar amplifiers exhibit typically noise figures of 1.2 to 1.5dB. The voltage regulator is a commercial Silicon integrated circuit. Both IF amplifier and regulator are mounted on hybrid thick film circuits. Further work to increase the output power of the oscillator to the 10 to 15 dBm range is underway.

A summary of results obtained in the evaluation of the downconverter is shown in Table 2.

The higher receiver noise figure of 9.5 dB SSB is due primarily to the fact the mixer is heavily driven by the local oscillator. The 20 dBm drive level exceeds the desired range from 10 to 15 dBm. The conversion loss of the mixer is typically 6.5 dB. For an IF amplifier gain of 20 dB the conversion gain of the receiver is approximately 13 dB. The dynamic range of the downconverter is shown in figure 11. For IF frequencies of 300MHz and 700MHz, conversion loss begins to rise at a rate of 0.5 dB per dB when the input power exceeds 5 dBm. The monolithic downconverter has been exposed to RF input levels of 300mW without experiencing any degradation.

| Parameter | Design Goal | Measured Response |
|---|---|---|
| Signal Frequency | 34 to 35 GHz | 34.5GHz |
| SSB Noise Figure | 9.5dB | 9.5dB |
| Input VSWR | 1.2 : 1 | 1.22 : 1 |
| Input Power for 1dB Compression Point | 0dBm | 5dBm |
| Local Oscillator Frequency | 33.7 to 35.3GHz | 34.8GHz |
| Local Oscilator Output Power | 10 to 15dBm | 20dBm |
| LO to RF Port Isolation | >25dB | 27dB |
| IF Port Impedance | 50 ohm | 80 ohm |
| Conversion Loss | 7.0dB | 6.5dB |

**Table 2 - Summary of Downconverter Performance**

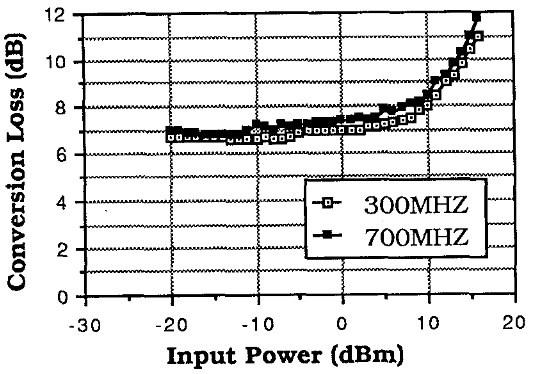


**Figure 11 - Dynamic Range of GaAs Downconverter Circuit**

The receiver in figure 10 illustrates an implementation in which monolithic circuit technology was used to reduce the cost of the downconverter, the most expensive item. The present implementation does capitalize on significant features of the technology available today Further cost reduction will the achieved with the fully monolithic downconverter at a later time..

## Conclusions

A comprehensive approach has been taken in the development of millimeter wave receivers to meet the described objectives. Monolithic mixers with state-of-the-art DBS noise figures in the range of 4 to 5 dB have been fabricated in production. Projected unit cost are in the tens of dollar. Integration of this result in the interim downconverter enables the fabrication of millimeter-wave receivers of competitive RF performance using monolithic technology available today.

The present work also established a number of results which are pre-requisites for the integration of fully monolithic downconverters. We demonstrated the feasibility of selective epitaxy for combining mixer and Gunn epitaxial layers at different locations on the wafer and validation of the process sequence for combining the fabrication steps of mixers and Gunn diode oscillators. These results will enable the integration of the fully monolithic downconverters as higher power local oscillators are developed.

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