A 30 GHz MONOLITHIC SINGLE BALANCED MIXER WITH INTEGRATED DIPOLE RECEIVING ELEMENT

S.J. NIGHTINGALE, M.A.G. UPTON, U.K. MISHRA, S.C. PALMATEER AND P.M. SMITH

GENERAL ELECTRIC COMPANY, ELECTRONICS LABORATORY, SYRACUSE, NY 13221

Abstract

A 30 GHz monolithic low noise balanced mixer has been developed using an integrated 'bow tie' antenna/WG transition and low parasitic Mott diodes. The diodes and mixer circuit were developed on General Electric grown MBE material and were fabricated using a plated air bridge technology. Measurements on the diode at DC and RF showed that the zero bias junction capacitance was 0.025 pF and the series resistance was 10 ohms. A conversion loss of 6 dB was measured at 30 GHz with a 1 GHz IF.

Introduction

This paper will describe the design and performance of a monolithic 30 GHz mixer and antenna/WG transition on GaAs. The mixer was intended for use in EHF phased array modules for space applications and a variety of designs were considered bearing in mind the requirement for high performance and low cost. Although the original requirement was for a communication link at 30 GHz, it was decided at the outset to select an approach that could be easily scaled to higher frequencies such as 44, 60 and 94 GHz without any significant compromise in RF performance. Previous experience at higher frequencies has shown that it was often difficult to make a satisfactory transition to an MMIC with repeatable performance. It was therefore decided to investigate an approach where the transition was incorporated onto the chip in the form of a receiving element or antenna which could act as a free space receiving element or as part of a transition to a rectangular waveguide. A second consideration was that the transmission lines be readily compatible with the coplanar realization of the diodes. Studies were made of different forms of transmission lines including microstrip, coplanar waveguide and coplanar strips, and a comparison was made between them in terms of impedance range, normalized guide wavelength and conductor and dielectric losses. In general it was found that from an electrical standpoint the most significant difference was in the impedance ranges which could be realized with acceptable loss. It was found that the edge coupled lines such as coplanar waveguide and coplanar strips had practical impedance ranges that were about twice those for broadside coupled lines such as microstrip for given values of loss. In view of the coplanar format of the diode and the coplanar receiving elements which showed promise the main part of the mixer circuit was designed using coplanar transmission lines.

Mixer Circuit Design

A planar circuit for the mixer and antenna was designed and this is shown in Figure 1. Apart from a groundplane for the microstrip elements, all the metallization for critical conductor geometries and the devices was on one side of the substrate. A balanced dipole 'bow-tie' antenna was selected feeding a 100 ohm balanced coplanar strip transmission line and the mixer design was assessed with a 'bow-tie' as a free space receiving element and as a transition to waveguide as shown in Figure 2.

The two most important factors in a mixer design are: 1) the nonlinear element, and 2) the embedding structure or circuit surrounding the device. The two are interdependent and therefore it is usual to specify one and design the other around it. A device was designed which had optimum characteristics for operation in the 100 ohm coplanar strip transmission line at 30 GHz. The two most important parameters in the device are: 1) the zero bias junction capacitance, and 2) the series resistance. The tradeoffs between the two were established from previous work and a junction capacitance of 0.025pF determined.

A Mott diode was chosen for the nonlinear device. The Mott diode is a form of Schottky diode in which the active layer is made very thin so that it remains virtually fully depleted over a wide range of junction voltages and hence over the LO cycle. This factor is important when the mixer is operated with a low LO power when parametric effects, such as are encountered in a conventional Schottky diode, can cause a significant increase in the mixer noise figure.

The mixer circuit is of single balanced design where the signal and LO are mutually isolated due to the circuit geometry and not due to the use of filters. The signal is fed to the diodes via a balanced line in coplanar strips. The mixer proper is formed at the junction between the coplanar line (with reduced width groundplanes) and the coplanar strips. The diodes are mounted at this junction which operates in a similar manner to the coplanar slotline junction commonly used in hybrid circuits. The slots formed either side of the coplanar line are made to be an integer number of half wavelengths long at the signal frequency in order to provide an open circuit plane at the diodes ($\lambda/2$ in this case). A transition between the microstrip line and the coplanar line is achieved by grounding the finite groundplane of the coplanar lines with quarter wavelength stubs in microstrip. In addition to overcoming the requirement for via holes this type of transition is important because it allows a DC voltage to be developed across the diodes. This is necessary in order to establish the optimum operating point on the diode VI characteristic to ensure minimum conversion loss and noise figure. The DC bias is supplied via low pass hi-lo filters realized in microstrip. The LO is connected to the coplanar line via a transition where the top conductor is common and the finite width groundplanes are grounded to the underneath groundplane using quarter wavelength microstrip stubs mounted at the transition point. A high pass quarter wavelength coupled line filter provides DC isolation between the diodes and the LO and also prevents the LO from loading the IF signals emerging from the mixer. A simple line and stub filter is used to extract the IF and provide over 30 dB of LO isolation.

Fabrication

The monolithic single balanced mixer was fabricated on General Electric grown MBE material. This layer structure consisted of a 3 micron thick n^+ layer doped at 2×10^{18} cm^{-3} followed by a 0.2 micron thick layer doped at 5×10^{16} cm^{-3} grown on undoped LEC substrates. The process sequence is as follows. The cathode contact was formed by etching down to the n^+ layer and defining the ohmic contact metal by a lift-off technique. After alloying the AuGeNi contact, the devices were isolated by etching 4 micron deep mesas. Next, contact areas were defined on the top and at the bottom of the mesa to form the cathode contact pad. At the same time, the anode contact was defined on top of the mesa along with a contact pad on the semi-insulating substrate. The Schottky barrier was defined by sputtering TiW and Au. The Schottky metal formed the base metal layer for the following plating step which defined the air bridge between the Schottky barrier and the pad. Next, the circuit metallization was defined by a conventional plating process. The final step in fabrication was polishing the wafer down to a thickness of 100 microns and completing the backside metallization process, again by a plating technique. This metal provided the ground plane for the microstrip areas and did not exist under the coplanar lines feeding the antenna.

Figures 3a and 3b are SEM micrographs of a typical Mott diode and illustrate the three most notable features of the technology employed:

1. The air bridge interconnect between the active anode and the contact pad at the mesa bottom, minimizes the parasitic capacitance commonly observed when a conventional dielectric assisted crossover is used to run the anode finger over the mesa edge (Figure 3a).

2. The thick mushroom shaped anode finger which is naturally generated by the plating technique employed, allows one to have a small active footprint (1 micron) with a thick feed line (see

Figure 3b). This enables one to have a small capacitance coupled with a low metal resistance which is necessary for low loss.

3. A more subtle advantage of the air bridged diode process is that it does not depend on the critical lipped resist profile which is necessary for lift-off. Hence, to a first order, the technology developed is independent of the mesa height employed which is untrue for a lift-off process.

DC and RF Test Results

Both DC and RF wafer probing of discrete Mott diodes was performed on approximately 50 devices. DC measurements indicated the diodes had a reverse breakdown of about -7V, and by accurately measuring the V-I characterstic the series resistance was determined to be 10 ohms and the ideality factor about 1.08.

A Cascade Microwave Model 42 probe station was used to make small signal one port S-parameter measurements for shunt mounted diodes over the frequency range 2-18 GHz.

Figure 4 shows Smith chart plots of S as the forward bias was increased from 0V to 1.08V where the current was 20 mA. The response before the diode starts conducting indicates a small capacitance. As the bias voltage is increased the resistance becomes more and more dominant and the response is seen to move across the Smith chart towards a short-circuit. When the current through the diode was 20 mA, the plot shows a series resistance of about 10 ohms.

A simple equivalent circuit for the diode was calculated from the one-port S-parameters for different bias conditions and a zero bias equivalent circuit is shown in Figure 5. The element values in the circuit were obtained by computer optimization of the measured versus modelled S-parameters. The starting values for L , C and C were obtained from the physical geometry of the device and processing parameters and the series resistance R was calculated from DC measurements.

The zero bias cut-off frequency of the diodes was determined to be 640 GHz. Figure 6 shows the variation of junction capacitance as a function of junction voltage for both the actual Mott diode and a theoretical Schottky. The Mott diode clearly shows flatter capacitance variation with voltage, being approximately 0.025 pF from -6V to +0.5V.

Figures 7 and 8 show the two portions of the waveguide fixture sketched in Figure 2. The GaAs substrate was mounted on alumina for mechanical strength using a non-conducting cement. The complete circuit was mounted in the fixture as shown in Figure 8.

Measurements were made of conversion loss as a function of LO power with a 30 GHz LO and a 31 GHz signal producing a 1 GHz IF. These are shown in Figure 8. The variable backshort and inductive tuning screws were adjusted for minimum conversion loss and the DC bias voltage was optimized for each LO setting. A single sideband conversion loss of 6 dB (including fixture losses) was measured with 10 dBm (10 mW) of LO power.

Conclusion

A 30 GHz monolithic low noise mixer has been described using an integrated "bow-tie" antenna/WG transition and low parasitic Mott diodes. Although the design requires further development to compact and improve the passive circuits, initial measured results for the first design are encouraging. This design incorporates tuning elements in the waveguide mount and can be made compact as the circuit is mounted broadside across the waveguide.

Acknowledgments

The authors wish to acknowledge the following: Dr. N.V. Dandekar for discussions on lithographic techniques, Helen DeOrio for technical assistance, and B.K. Mitchell for his work on the 'bow tie' antenna.

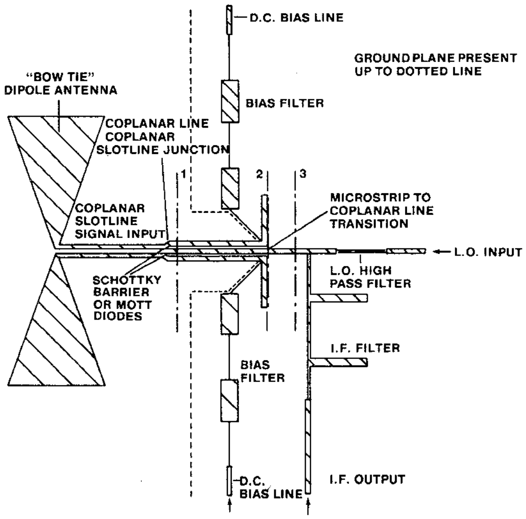


FIGURE 1. A 30 GHz MONOLITHIC PLANAR SINGLE BALANCED MIXER INCORPORATING A 'BOW-TIE' ANTENNA/WG TRANSITION ELEMENT

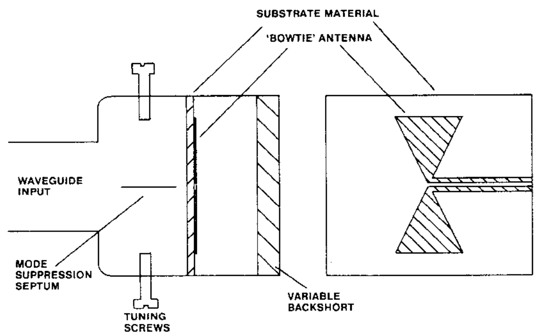
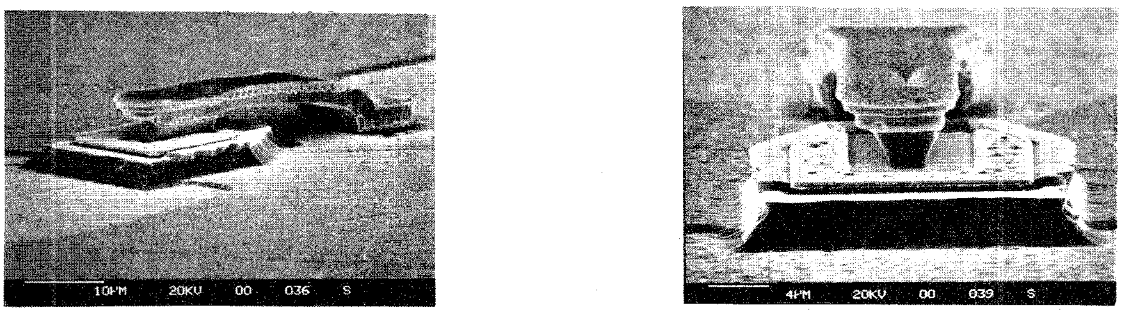
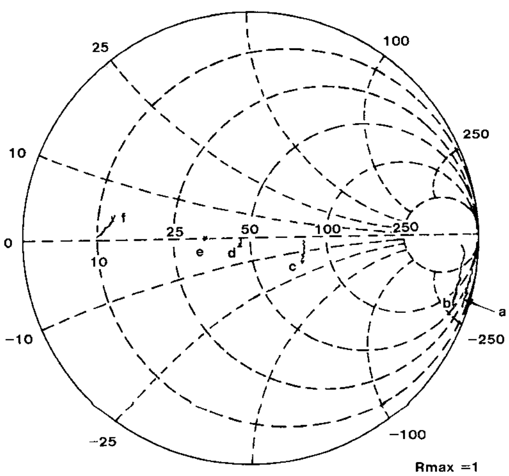


FIGURE 2. A SKETCH SHOWING THE KEY FEATURES OF A WAVEGUIDE TO BALANCED LINE TRANSITION USING A 'BOW-TIE' ANTENNA ELEMENT



3a) 3b)

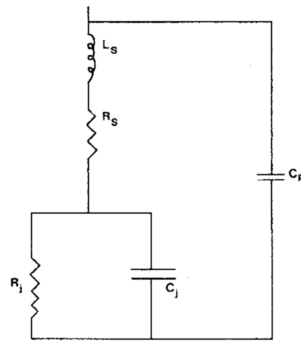
FIGURE 3 SEM MICROGRAPHS OF A TYPICAL MOTT DIODE



BIAS CONDITIONS

a) V = 0V, I = 0mA
b) V = 0.6V, I ≈ 0mA
c) V = 0.72V, I = 0.5mA
d) V = 0.75V, I = 1.0mA
e) V = 0.77V, I = 1.5mA
f) V = 1.08V, I = 20.0mA

FIGURE 4 S_{11} OF A SHUNT MOUNTED MOTT DIODE AS A FUNCTION OF DC BIAS VOLTAGE.



L_S = 0.01 nH
R_S = 10.0 Ω (TYPICALLY)
C_P = 0.007 pF
C_j = 0.025 pF (TYPICALLY)

$I_S = I_O (e^{\frac{q}{nkT} V_j} - 1)$
I_O = 0.5 pA
n = 1.076

FIGURE 5. DIODE EQUIVALENT CIRCUIT

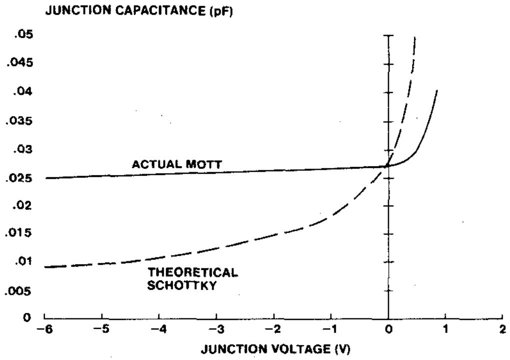


FIGURE 6. CAPACITANCE-VOLTAGE CHARACTERISTIC OF MOTT AND SCHOTTKY DIODES

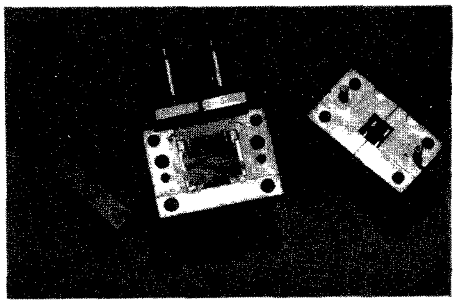


FIGURE 7 DISASSEMBLED MIXER

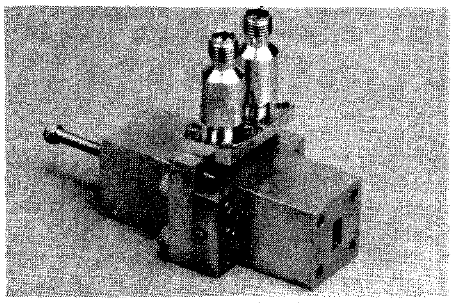


FIGURE 8 COMPLETE EHF MIXER

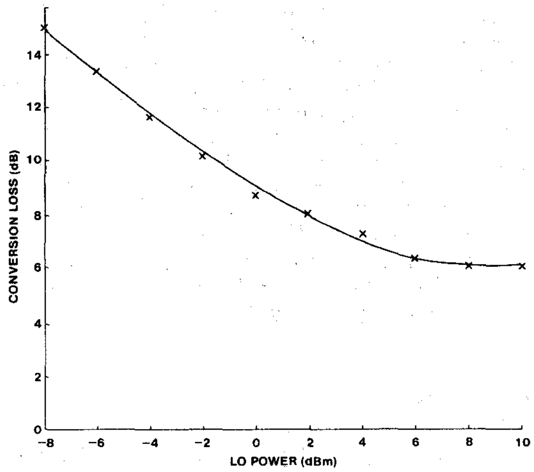


FIGURE 9. CONVERSION LOSS VERSUS LO POWER OF 30 GHz MONOLITHIC SINGLE BALANCED MIXER