Dual Function Mixer Circuit for Millimeter Wave Transceiver Applications*

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ABSTRACT

A monolithic mixer circuit capable of performing either a receiver or transmitter function has been fabricated. The mode of operation is determined by applying either forward bias or reverse bias to a pair of mixer diodes. The circuit integrates Schottky-barrier diodes, bias lines, Ta_2O_5 blocking and by-pass capacitors, a radial line stub filter and a microstrip branch-line coupler. For the receiver function the unit exhibits a conversion loss of 6.5 ± 0.5 dB from 34 to 36 GHz. For the transmitter function the circuit directs the signal from the local oscillator port to the antenna port with an insertion loss of approximately 2 dB at 33.5 GHz over a bandwidth of 1 GHz.

INTRODUCTION

The efficient implementation of the transmit/receive (T/R) function is a challenge in monolithic transceiver design at millimeter-wave frequencies. In contrast to hybrid designs, monolithic fabrication and packaging approaches do not appear to be amenable to the use of circulators. As a result, implementation such as the one depicted in Fig. 1 is being considered.[1] In this circuit, a double-pole double-throw switch determines the T/R function. For transmission the output signal of the voltage controlled oscillator (VCO) is connected directly to the antenna. For reception the oscillator and the antenna are connected to the input ports (R) of the heterodyne receiver with the VCO tuned to the local oscillator (LO) frequency.

This circuit is practical at lower microwave frequencies because it can be implemented with GaAs-FET switches. For example, losses on the order of 1 dB have been achieved at 10 GHz with passive FET switches.[2] Active dual-gate FETs switches have provided gains in the range of 8 to 1 dB at the same frequency.[3] However GaAs-FET switches have higher insertion losses at millimeter-wave frequencies. The reported insertion losses for single FET switches in the 27 to 30 GHz range are from 2 to 3 dB.[4]

As a result, the high insertion loss of the double-pole double-throw switches in Fig. 1 will degrade the noise figure of the receiver and reduce the output power of the transmitter at millimeter-wave frequencies.

A dual function monolithic circuit which avoids the use of double-pole double-throw switches has been fabricated and tested. A photograph of the circuit is shown in Fig. 2. This monolithic circuit is capable of performing either as a receiver or as a transmitter switch. The mode of operation is determined by applying either forward bias or reverse bias to a pair of mixer diodes. The present circuit is the first monolithic implementation using this approach. This concept has also been implemented in hybrid circuits using packaged diodes[5] mounted in waveguide and beam-lead diodes soldered in fin-line circuits.[6] The mixer diodes can also be used for pulse modulation in the transmission mode, as has been demonstrated in the hybrid implementations.

CIRCUIT CONFIGURATION

The circuit shown in Fig. 2 integrates a microstrip branch-line coupler,[7] a radial-line stub filter,[8] Schottky-barrier diodes[9] and Ta_2O_5 capacitors.[10] Each output arm of the branch-line coupler is connected to a Schottky-barrier diode through a Ta_2O_5 blocking capacitor (3 pF). Bias for the diodes is provided by lines connected to Ta_2O_5 by-pass capacitors (14 pF), which are also included in this circuit. The dimensions of the die are 2.0 mm by 2.0 mm.

Control is achieved by applying either forward or reverse bias to the diodes as shown in Fig. 3. If the diodes are forward biased, resistive loads are presented to the output arms, and both signal and LO power are coupled to the diodes. The circuit operates as a balanced mixer, similar to that described previously.[8] However, because forward bias is applied to the diodes, the LO power requirements are reduced significantly. If the Schottky-barrier diodes are reverse biased, reactive loads are presented to the output arms of the branch line coupler. Since the reactive loads are identical by design, the reflected waves at the output arms of the coupler add destructively at the LO port and constructively at the antenna port. As a result, the circuit functions as a transmitter switch, directing signals incident on the LO port to the antenna port.

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FABRICATION SEQUENCE

The fabrication sequence of the dual function mixer circuit uses 8 mask levels, of which 3 levels are associated with the fabrication of the Ta_2O_5 capacitors and 5 levels are used for the fabrication of the mixer diode and microstrip circuits. Figure 4 is a diagram illustrating the eight-step fabrication sequence. Wafer processing begins with the formation of ohmic contacts (step 1). Windows are opened in appropriate areas and the n-layer is etched to expose the underlying n^+-layer. The Au-Ge-Ni ohmic contact metallization is evaporated and patterned by photoresist lift-off. The devices are then isolated by a combination of mesa etching (step 2) and proton bombardment (step 3). This two-step process was developed because it enables the use of conducting layers with thicknesses greater than the 4-µm penetration depth of the 400 keV protons used in the proton isolation. Composite layers for the Ta_2O_5 capacitor are then sputter deposited and defined using photoresist lift-off (step 4). The Au layer and the underlying Ta layer are defined by wet etching and by plasma etching, respectively (step 5). Trimming of capacitance can be incorporated at this step.

Access to the bottom electrode of the capacitor is provided by etching the Ta_2O_5/Ta layers with a CF_4 plasma in a barrel type reactor (step 6). Etching was performed at a power level of 150 mW and a pressure of 2 Torr. A polyimide layer is then defined to provide support for the connection to the top layer of the capacitor (step 7), and the anode for the mixer diode and the circuit elements are formed by photoresist lift-off (step 8). In our prior work[7,9] transmission lines were fabricated by evaporating a conductive base layer, defining and electroplating circuit elements, and stripping the base layer. The lift-off process is simpler, requiring only photolithography and metal deposition.

RF RESULTS

Measurements were first performed on the monolithic circuit in the receiver configuration. Figure 5 shows conversion loss as a function of IF frequency for two values of DC bias applied to the diodes. With no externally applied DC bias and 18 mW of LO power at 34 GHz, the conversion loss was 6.5 ± 0.5 dB over a bandwidth of 1 GHz. With an applied external bias of 1 V in the forward direction across the diodes, the conversion loss increased to between 7.5 and 8 dB over a similar bandwidth. However, the LO power requirement was reduced to 5 mW. Figure 6 shows the double sideband (DSB) noise figures as a function of IF frequency for the same mixer. This measurement includes the noise of an external IF amplifier, which had a noise figure in the range of 2.0 to 2.5 dB from 1 to 2 GHz. With no bias voltage applied externally, the LO power required for minimum noise figure was 18 mW. The corresponding noise figure is in the range of 7 to 8 dB from 1.0 to 1.7 GHz. With a 1 V forward bias the LO power required for minimum noise figure was 5 mW and the noise figure increased ~0.5 dB over the same frequency band. A reduction of LO power to 2 mW produced only a modest 0.2 dB increase in noise figure.

In the transmit configuration a reverse bias of 6 V was applied across both diodes. Figure 7 shows the insertion loss and return loss from 33 to 36 GHz with an input power of 150 mW. The measured insertion loss is typically ~2 dB in the frequency range of 33 to 34.5 GHz, which compares favorably with the 4 to 6 dB loss associated with the conventional approach shown in Fig. 1. The corresponding return loss is greater than 14 dB over the above frequency range. This indicates that the reversed-biased diodes, blocking capacitors, and radial line stub present nearly identical reactive loads to the output arms of the coupler.

CONCLUSION

A monolithic circuit capable of performing either a receiver function or a transmitter function has been fabricated for the first time. Conversion losses of 6.5 ± 0.5 dB (34-35.6 GHz) in reception and insertion losses of ~2 dB (33-34.5 GHz) in transmission compare favorably with T/R switch implementations using FETs at the present time. This circuit design and fabrication technology can be extended to higher millimeter-wave frequencies.

Both conversion loss and noise figure are approximately 1 dB higher in the dual function mixer circuits than in monolithic mixers fabricated in our laboratory.[9] The difference in performance is attributed to the insertion loss of ~0.5 dB associated with the large 3 pF Ta_2O_5 blocking capacitors. Smaller capacitors with thicker gold electrodes are presently being incorporated to reduce skin effect losses. It is also possible to increase the power handling capability of the circuit in transmission by lowering the doping concentration of the n layer, because this will increase the breakdown voltage of the mixer diodes. However, this may degrade the conversion loss of the mixer diodes so that further work in this area is necessary.

Monolithic circuits at millimeter-wave frequencies require the optimal use of devices and circuit elements for the implementation of receiver and transmitter functions. In the present circuit the Schottky barrier diodes are used as mixer diodes in the receiver function and as control diodes in the transmitter function. The branch-line coupler is used to combine the LO and antenna signals in reception and as part of a reflective switch in transmission. These dual functions of devices and components enable the realization of a monolithic circuit in which a large increase in functional complexity is obtained with only a slight increase in circuit complexity.

REFERENCES

1. A. Chu, W. E. Courtney, and L. J. Mahoney, "Monolithic circuits for millimeter-wave systems," Microwave Journal, vol. 26, no. 2, p. 28, Feb. 1983.

2. W. V. McLevige and V. Sokolov, "Resonated GaAs FET devices for microwave switching," IEEE Trans. Electron Devices, vol. ED-28, no. 2, p. 198, Feb. 1981.

3. J. L. Vorhaus, W. Fabian, P. B. Ng, and T. Tajima, "Dual gate GaAs FET switches," IEEE Trans. Electron Devices, vol. ED-28, no. 2, p. 204, Feb. 1981.

4. V. Sokolov, P. Bauhahn, J. Geddes, T. Contolatis, and C. Chao, "A GaAs monolithic phase shifter for 30 GHz applications," in 1983 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Tech. Dig., p. 40, 1983.

5. Y. Matsuo, Y. Akaiwa, and I. Takase, "A compact 60 GHz transmitter-receiver," IEEE Trans. Microwave Theory Tech., vol. MTT-24, no. 11, p. 794, Nov. 1976.

6. R. Mehran, J. Ludewig, and L. Szabo, "Integrated Ka-Band finline Mixer/Modulator," Electron. Lett., vol. 20, No. 22, p. 934, Oct. 1984.

7. T. Okoshi, T. Imai, and K. Ito, "Computer-oriented synthesis of optimum circuit pattern of 3-dB hybrid ring by the planar circuit approach," IEEE Trans. Microwave Theory Tech., vol. MTT-29, no. 3, p. 194, March 1981.

8. A. Chu, W. E. Courtney, L. J. Mahoney, R. A. Murphy, and R. W. McClelland, "Monolithic frequency doublers," in 1983 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Tech. Dig., p. 45, 1983.

9. A. Chu, W. E. Courtney, and R. W. Sudbury, "A 31 GHz monolithic GaAs mixer/preamplifier circuit for receiver applications," IEEE Trans. Electron Devices, vol. ED-28, No. 2, p. 149, Feb. 1981.

10. A. Chu, L. J. Mahoney, M. E. Elta, W. E. Courtney, M. C. Finn, W. J. Piacentini, and J. P. Donnelly, "A two-stage monolithic IF-Amplifier integrating a high dielectric constant capacitor," in 1982 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Tech. Dig., p. 61, June 1982.

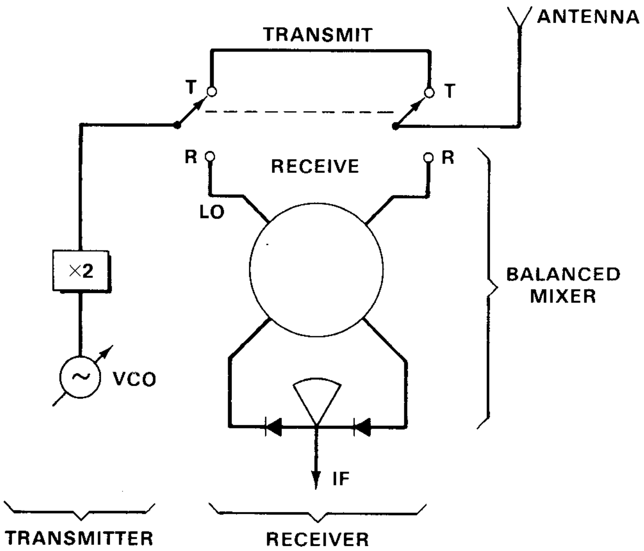

Figure 1. A balanced-mixer/transceiver implementation using double-pole double-throw switches.

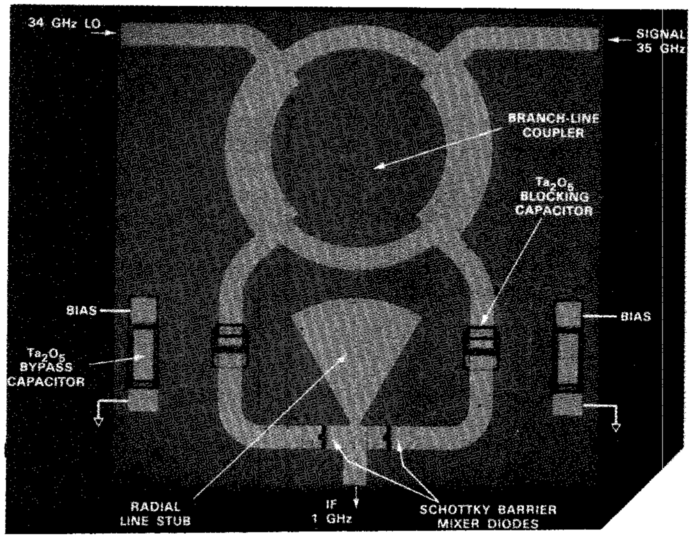

Figure 2. A dual function mixer circuit for transceiver applications at millimeter-wave frequencies.

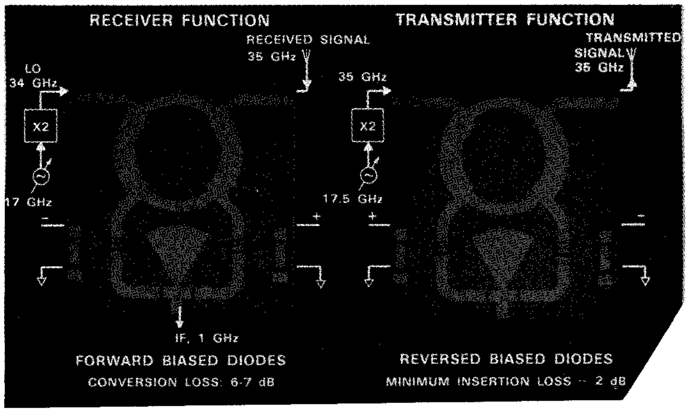

Figure 3. Transmitter and receiver configurations for the dual function mixer circuit.

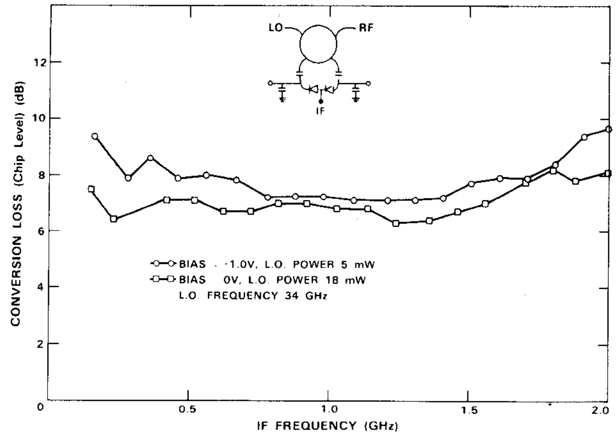

Figure 5. Conversion loss of mixer as a function of IF frequency for two bias voltages.

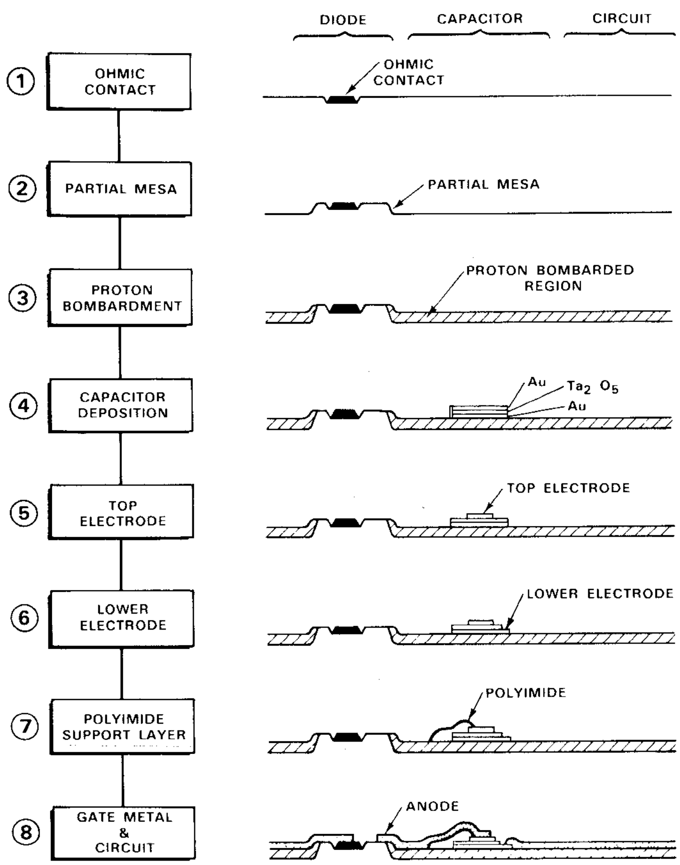

Figure 4. Fabrication sequence for dual function mixer circuit. The eight steps at the process are illustrated schematically.

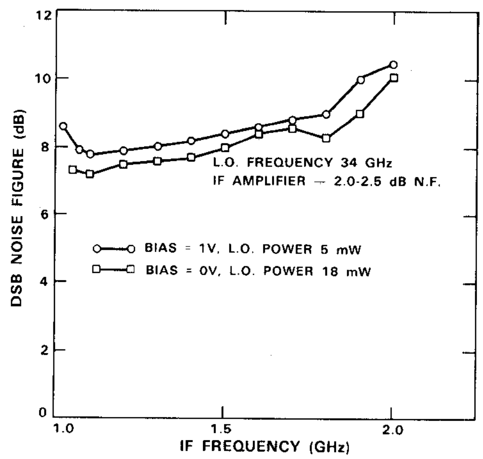

Figure 6. Noise figure of mixer as a function IF frequency for two bias voltages.

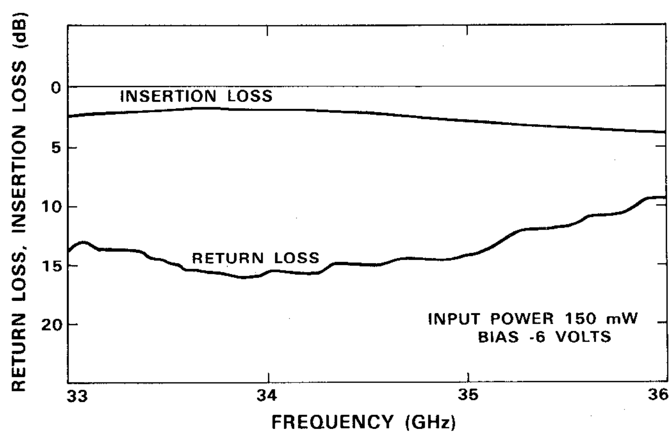

Figure 7. Insertion loss and return loss of the dual function mixer circuit in transmission mode.