GaAs MONOLITHIC FREQUENCY DOUBLERS WITH SERIES CONNECTED VARACTOR DIODES*

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ABSTRACT

GaAs monolithic frequency doublers using series connected varactor diodes have been fabricated for the first time. Output powers of 150 mW at 36.9 GHz with 24% efficiency and 300 mW at 24.8 GHz with 18% efficiency have been obtained. Peak efficiencies of 35% at output power levels near 100 mW have been achieved at both frequencies. Both K-band and Ka-band frequency doublers are derived from a lower power, single-diode design by series connection of two diodes and scaling to achieve different power and frequency specifications. Their fabrication was accomplished using the same process sequence.

INTRODUCTION

Monolithic frequency doublers integrating planar varactor diodes and microstrip circuits on a GaAs substrate were recently reported for the first time.[1] These doublers are intended for millimeter-wave receiver and transmitter applications requiring large numbers of units, for which the low cost potential of monolithic circuits is of primary importance. The reported frequency doublers provide power levels in the range of tens of milliwatts, which are adequate for local oscillator applications in heterodyne receivers. For many transmitter applications, however, power levels in excess of 100 mW are necessary. To meet these higher power requirements, we have designed and fabricated frequency doublers with series connected diodes. The connection of varactor diodes in series to increase harmonic power has been used in waveguide circuits.[2,3] The application of this technique in a monolithic circuit is now reported for the first time.

The present paper covers device and RF circuit design, fabrication, and RF test results of monolithic frequency doublers using series connected diodes.

DEVICE AND RF CIRCUIT DESIGN

Figure 1 is a photograph of a monolithic frequency doubler with two varactor diodes connected in series. The two diodes can be seen near the center of the circuit. The input and output matching circuits consist of quarter-wave transformer sections with open circuited shunt radial line stubs. The radial line stubs are resonant at input and output frequencies. Their locations are selected to reflect appropriate impedances to the plane of the diodes.

The design of the two-diode monolithic doubler was derived from the design of the single-diode doubler[1] shown in Figure 2. In general, the power handling capability of varactor diode multipliers is proportional to the square of the reverse breakdown voltage (V_{BR}) of the diode. Therefore, an effective and practical way to increase output power of a single-diode frequency doubler is by replacing the single diode with a number of diodes connected in series. This replacement of active devices does not require any modification of the embedding circuit. For example, if n diodes with breakdown voltage V_{BR} are connected in series, their overall breakdown voltage is nV_{BR} and the output power would be proportional to $(nV_{BR})^2$. This limit is approachable to the extent that the impedance and RF losses presented by the series connected diodes to the embedding circuit are identical to those of the original single diode.[1] Thus, to maintain the impedance invariant, the active area of each diode in the series connection has to be increased by a factor of n in order to preserve the overall values of capacitance and series resistance.

Figure 3 shows a detailed view of the two planar diodes connected in series. The diameter and area of each anode are ~38 μm and ~1120 μm^2, respectively. The anode area of the single-diode doubler was ~560 μm^2. The overall reverse breakdown voltage of the series connected diodes is typically 30 V, as shown by the inset in Figure 4. The zero bias capacitances of the diodes are approximately 0.3 pF, as indicated by the capacitance-vs-bias voltage curve in Figure 4.

To increase the power handling capability of the single-diode doubler (Figure 2), it was only necessary to replace the single diode by a diode pair, without making any changes in the embedding circuit. As shown in Figure 1, however, in the two-diode doubler the input and output resonant stubs were changed from a conventional open circuited transmission line design to a radial line design. This change was made to increase the bandwidths of both input and output resonant circuits.

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The design of radial line stubs is not yet fully understood. At lower frequencies and for low dielectric constant substrates, Vinding's solution[4] of the equations for radial electromagnetic waves with magnetic walls at the boundaries provides reasonable predictions. However, there are substantial discrepancies for dielectric constants as high as that of GaAs. Figure 5 shows a comparison of theory and experiment for a ceramic substrate[5] with ε_r=13, the same dielectric constant as GaAs. Experimental resonant frequencies were obtained from the measurement of 60° radial lines fabricated by applying adhesive copper foil to the substrate.[5] The theoretical curve is based on Vinding's approximate solution.[4] The discrepancy between calculated and measured resonant frequencies is due to the complex open boundary conditions of the radial line stubs, which cannot be approximated successfully over a wide range of frequencies and dielectric constants by using elementary assumptions and formulations. Further theoretical work in this area is underway. For the present, empirical curves such as the one in Figure 5 can be used for the design of circuits at millimeter wave frequencies through the use of scaling techniques.[1]

Flexibility in the design of frequency multipliers with respect to power handling capability is achieved by use of multiple diodes. Additional design flexibility is provided by the use of geometric scaling for modification of operating frequency. This technique has been used to fabricate Ka-band frequency doublers by scaling a Ka-band mask set by a factor of 5/7 from the K-band mask set. The substrate thickness of the Ka-band doublers was also reduced by this same factor, from 175 μm to 125 μm.

FABRICATION

The series connection technique permits the utilization of the same fabrication procedure for both single-and multiple-diode frequency doublers. Obviously the same procedure can also be used to produce scaled doublers if the wafers are thinned to an appropriate thickness. Consequently, monolithic frequency multipliers with different power and frequency specifications can be produced using the same fabrication sequence. This flexibility in fabrication, which has important economic implications, is a characteristic feature of the monolithic approach.

Highlights of the fabrication sequence are shown in Figure 6. For the sake of simplicity a single diode is represented in the illustrations. The devices are fabricated on a substrate prepared by using a vapor phase epitaxial reactor to grow the following GaAs epilayers on a semi-insulating GaAs wafer: an n^+ layer (2-3 x 10^{18} cm^{-3}) 3.5 to 4.0 μm thick, and an n layer (2 x 10^{16} cm^{-3}) ~1 μm thick. Both layers are doped with sulfur. Major fabrication steps are: (a) formation of ohmic contacts for the cathodes, (b) isolation of devices by a combination of mesa etching and proton bombardment, (c) formation of Schottky barrier anode junctions and plating of circuit elements. Each of these steps has been described previously.[1]

RF TEST RESULTS

The monolithic frequency doublers are mounted in a test fixture between two short sections of 50-Ohm microstrip line fabricated on 0.010" alumina substrates. The microstrip lines are connected to OSSM launchers.

The test results for a two-diode K-band frequency doubler (output frequency 24.8 GHz) are shown in Figure 7. The unit exhibited a maximum output power of 300 mW with a conversion efficiency of 18%. The peak efficiency of 35% occurs at a power of 100 mW. The test results for the two-diode Ka-band frequency doubler (output frequency 36.8 GHz) are shown in Figure 8. This unit exhibited a maximum output power of 150 mW with a conversion efficiency of 24%. The peak efficiency of 35% is obtained at 95 mW. The data presented pertain to performance at the chip level. They were derived from measured power levels at the connectors by accounting for losses in the test fixture.

CONCLUSIONS

Monolithic frequency doublers incorporating series connected diodes have been fabricated for the first time. Output powers of 300 mW at 24.8 GHz with 18% conversion efficiency and 150 mW at 36.8 GHz with 24% conversion efficiency have been obtained. Peak efficiencies of 35% have been achieved at output power levels near 100 mW at both frequencies. These circuits are of interest for millimeter-wave receiver and transmitter applications.

Both K-and Ka-band monolithic circuits with series connected diodes were derived from a single-diode design with lower output power capability. Increased output power was obtained by using series connection to double the reverse breakdown voltage, and the change in operating frequency was achieved by geometric scaling. Thus, a family of units with different power and frequency specifications can be derived from a basic single-diode design. Furthermore, the same process sequence can be used for fabricating all of these circuits.

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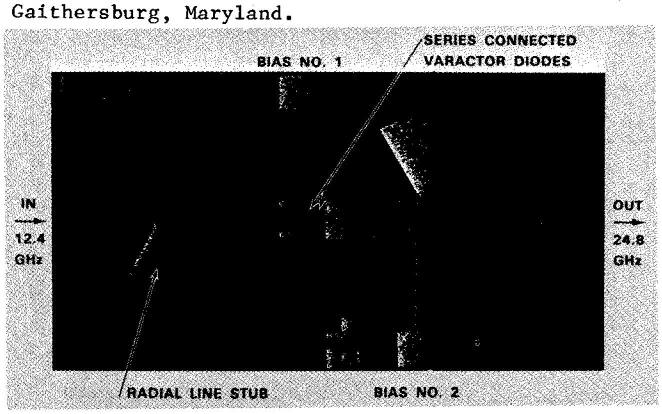

Figure 1. GaAs K-band monolithic frequency doubler with series connected varactor diodes. Two planar diodes are integrated with microstripline circuits, radial line stubs and bias lines. Dimensions of the die are 4 mm by 8 mm.

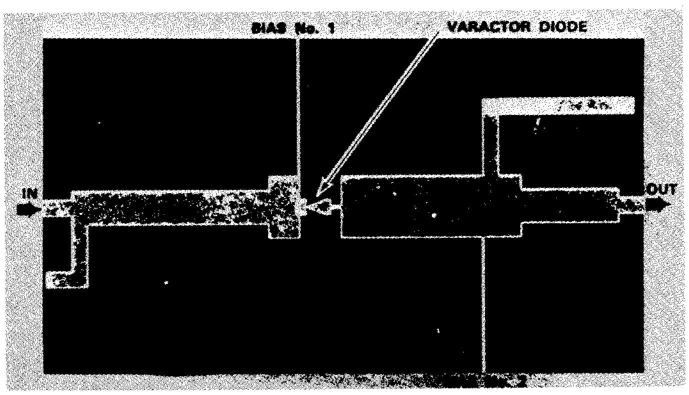

Figure 2. GaAs K-band single-diode monolithic frequency doubler. A varactor diode is integrated with microstripline circuits, open circuited stubs and bias lines. Dimensions of the die are 4 mm by 8 mm.

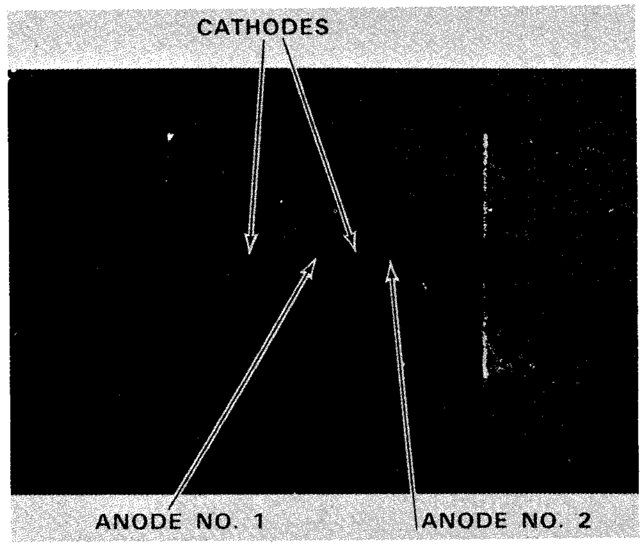

Figure 3. Monolithic planar varactor diodes connected in series. The series connection increases the overall breakdown voltage and the RF power handling capability of the diode pair.

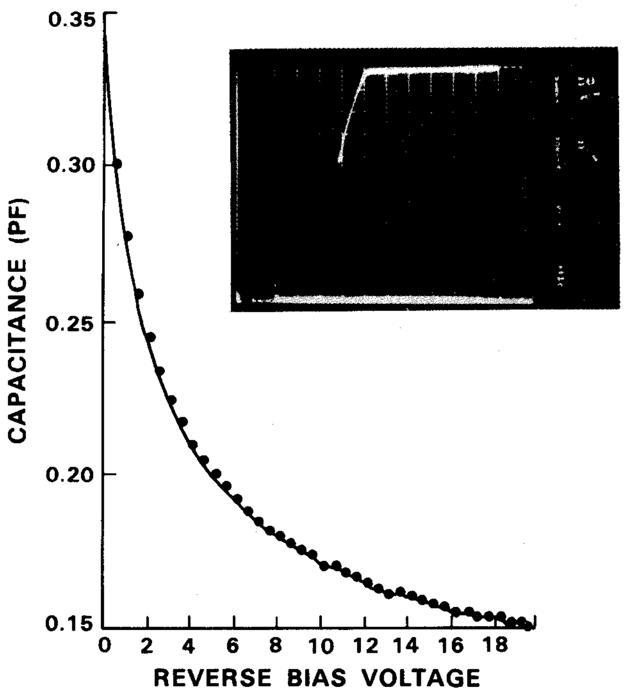

Figure 4. Junction capacitance vs reverse bias voltage of K-band varactor diodes in series. The inset shows reverse breakdown voltage of the diode pair.

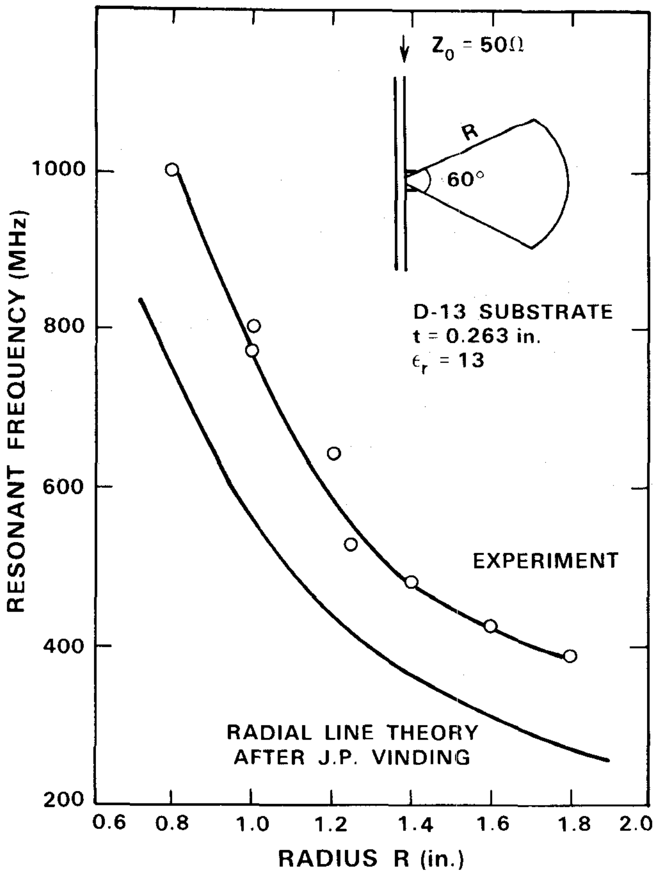

Figure 5. Theoretical and experimental resonant frequencies of 60° radial line stubs vs radius.

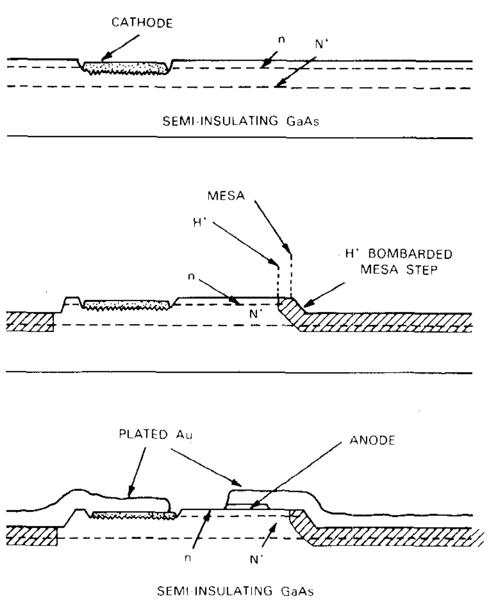

Figure 6. Highlights of fabrication sequence. (a) Ohmic contact formation, (b) Device isolation by mesa etching and proton bombardment, (c) Schottky barrier junction formation and circuit plating.

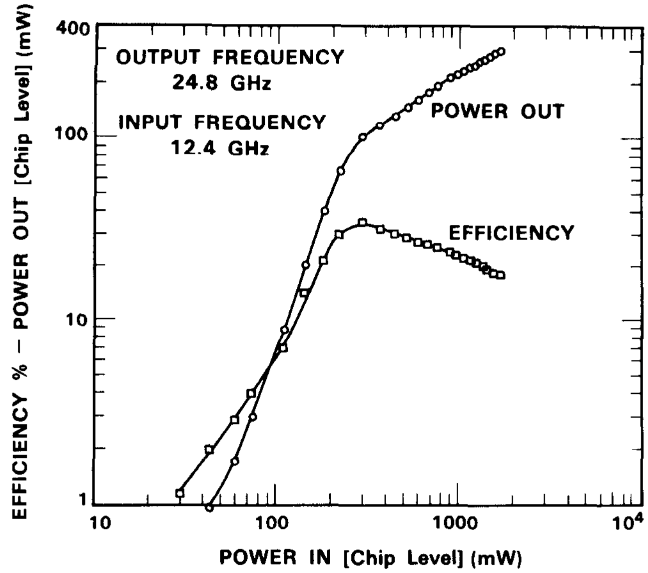

Figure 7. Output power and conversion efficiency of K-band 2-diode monolithic frequency doubler at the chip level as a function of input power.

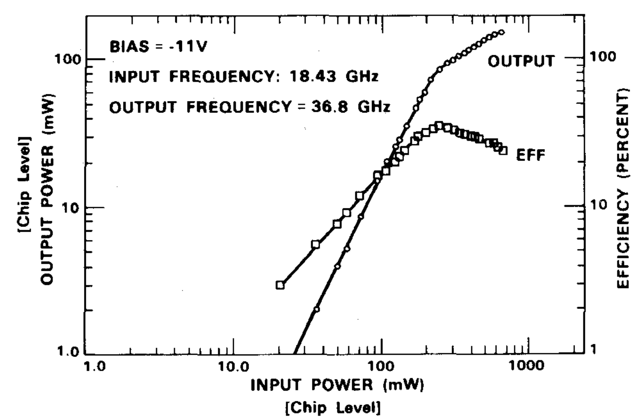

Figure 8. Output power and conversion efficiency of Ka-band 2-diode monolithic frequency doubler at the chip level as a function of input power.