RIGOROUS DESIGN OF A 94 GHZ MMIC DOUBLER

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Abstract—A 94 GHz monolithic microwave integrated circuit (MMIC) frequency doubler with 25% efficiency and 65 mW output power has been developed. Variations in the diode's performance as a doubler with its geometry and doping profile were analyzed for optimum efficiency and output power. Optimum doubler performance was obtained as a consequence of use of the optimized diode parameters resulting from this analysis. Measured results of the diode parameters as well as doubler response showed excellent agreement with the analysis. The doubler exhibits better performance than those reported in the literature at similar frequencies using an MMIC approach.

I. Introduction

Schottky-barrier diode frequency doublers have been widely used as power sources at microwave and millimeter wave frequencies to extend the range of maximum oscillation frequency (f_{max}) of the active devices. Theoretical analysis of frequency doublers has been intensively investigated [1]-[3]. This revealed a dependence of doubler performance on the varactor diode cut-off frequency, breakdown voltage and the diode input/output termination impedances. In millimeter wave transmitter applications, where high power handling capability is required, series connected [4] and stacked varactor diode [5] doublers have been used to increase breakdown voltage. However, the former approach degrades the doubler efficiency due to extra series resistance and the latter one is difficult for MMIC implementation.

Alternatively, the varactor diode structure parameters can be optimized to exhibit the higher cut-off frequency and breakdown voltage required for high efficiency and high output power. In general, to achieve high cut-off frequency, a heavily doped, small, and thin epilayer is necessary for the diode, which in turn limits the breakdown voltage, current flow and hence the power handling capability. Moreover, the diode n^+ layer need to be thick enough to reduce series resistance. In this paper, junction capacitance, parasitic resistance, including spreading resistance and skin effect, and breakdown voltage of a disk type varactor diode are analyzed. The optimized dimension and doping concentration are determined. Results of such analysis were used to develop a doubler circuit, which led to the state-of-the-art results for a 94 GHz MMIC frequency doubler.

II. Analysis and Design

Successful development of a doubler circuit hinges on proper design and accurate modeling of the varactor diode, which determine the intrinsic efficiency (conversion loss), and the maximum output power the doubler can achieve. The high frequency model of a Schottky barrier varactor diode consists of a resistance R_s, in series with the barrier admittance $(1/R_j + j\omega C_j)$. where R_j is in the kΩ range so the capacitance dominates the admittance at sufficiently high frequencies. The series resistance R_s consists of voltage dependent epilayer resistance, spreading resistance and contact resistance. At millimeter wave frequencies, skin effect has to be considered for maximum accuracy. For the mesa type diode structure having both contacts on top of the chip, the current through the device has to flow down from the anode and spread laterally around the base of the mesa before flowing out of the cathode. Assuming the cur-

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rent density is confined parabolically within a skin depth δ, the series resistance R_s is broken into several components and can be derived based on previous work [6]-[7]. The diode junction capacitance C_j and breakdown voltage V_B can also be estimated accurately [8]. The doubling efficiency η and maximum output power, P_{out}, of an abrupt junction varactor diode can be predicted from R_s, C_j and V_B by [1][9]

$$\eta = \frac{1 - 10.40\omega R_s C_{min}}{1 + 10.40\omega R_s C_{min}} \quad (1)$$

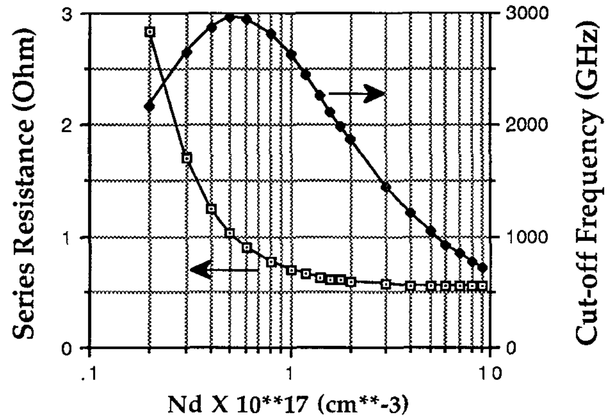
$$P_{out} = 0.0285\omega C_{min}(V_B + \Phi_0)^2 [1 - 10.40\omega C_{min} R_s] \quad (2)$$

where C_{min} is the junction capacitance at breakdown voltage V_B. The coefficients, 10.4 in equation (1) and 0.285 in equation (2) were obtained by solving the nonlinear charge equation in the diode junction [1].

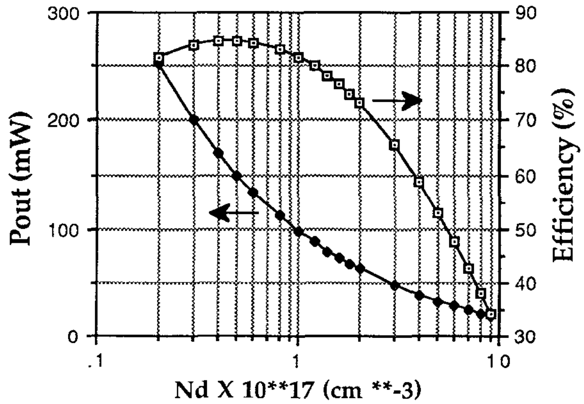
Variation of a varactor diode series resistance and cut-off frequency with the active layer doping concentration has been simulated and is shown in Figure 1a. Doubling efficiency and maximum output power of the diode as a function of doping concentration are shown in Figure 1b. The figure shows that an optimum epilayer doping concentration exists for maximum efficiency which coincide with the maximum cut-off frequency.

The design of the 94 GHz frequency doubler started with an analysis of the diode structure as depicted above for optimized efficiency and output power at 94 GHz with 350 mW input at 47 GHz. For a varactor diode with a 16 μm diameter Schottky contact, an active layer doping concentration of 7×10^{16} cm^{-3} was chosen for optimum efficiency as indicated by Figure 1b. The breakdown voltage of the diode was estimated to be 20.5 V. The thickness of the active layer was in turn determined to be 0.65 μm from the doping concentration and breakdown voltage so as to keep the depletion layer in the active region from penetrating into the substrate at full drive condition.

Figure 2 is the microphotograph of the 94 GHz MMIC doubler chip. Ideally, the input matching circuit is made transparent to the 47 GHz signal and shorts out all the harmonics generated by the nonlinearity of the diode; the output matching circuit allows maximum power at the second harmonic frequency being delivered to the load and rejects all other harmonics and the residual fundamental



(a)



(b)

Figure 1. (a) Series resistance and cut-off frequency, (b) Efficiency and output power as function of the active layer doping (Schottky contact diameter = 16 μm, n^+-layer thickness = 2.5 μm, and the active layer thickness is changed with the doping concentration to prevent depletion of the layer into the n^+ substrate at the breakdown voltage)

frequency signal. This input and output isolation can be approximately achieved by adding a $\lambda/4$ short stub (at 47 GHz) and a $\lambda/4$ open stub (at 47 GHz) at the input and output side of the diode, respectively. Since $\lambda/4$ at 47 GHz is equivalent to $\lambda/2$ at 94 GHz, the short stub creates an RF short at 94 GHz at the input side of the diode without affecting the impedance at 47 GHz. Similarly, the open stub generates an RF short at 47 GHz at the output side

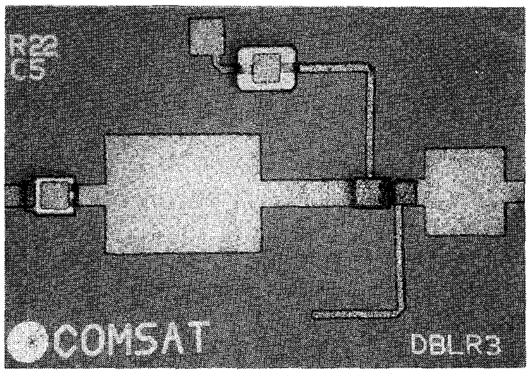


Figure 2. Microphotograph of the 94-GHz MMIC frequency doubler

of the diode without perturbing the impedance at 94 GHz. Since the diode is modeled as a voltage dependent capacitive impedance, inductive source and load terminations are required in order to resonate the diode junction capacitance to obtain maximum efficiency and output power. As shown in the figure, two transmission lines are employed at both input and output to resonate out the average junction capacitance of the diode and transform 50Ω impedance to the optimum diode termination resistance.

It is worthwhile to note that the efficiency and maximum power predicted by equation (1) and (2) assumes full drive (at breakdown voltage V_B) and neglects circuit loss and other parasitic elements associated with the device and circuit. In addition, RF power of the third and higher harmonics generated by nonlinearity of the diode are ignored in the expressions. For accurate modeling of the doubler response, more rigorous time domain or frequency domain nonlinear circuit analysis, such as SPICE and LIBRA, is necessary. Nonetheless, the results predicted by equation (1) and (2) provide extremely valuable information on diode parameters for optimum doubler performance. Some parameters of the varactor diode, together with measured results, are given in Table I. Simulated results of a 94-GHz doubler in LIBRA using the diodes are also presented in the table. Excellent agreement of the predicted values with the measured results was achieved, and validity of the analysis was verified.

Table I. Comparison of measured and predicted diode parameters and doubler performance.

Description		
Active layer doping	7×10^{16} cm^{-3}	
n^+ layer doping	8×10^{18} cm^{-3}	
Diameter of Schottky contact	16 μm	
Active layer thickness	0.65 μm	
n^+ layer thickness	2.5 μm	
	Predicted	Measured
Series resistance R_s	0.82 Ω	0.87 Ω
Zero-biased capacitance (C_{jo})	0.17 pF	0.17 pF
Breakdown Voltage (V_B)	20.5 V	18 V
Efficiency (η) @ 330 mW input	28.1%	19.7%
Output power @ 330 mW input	93 mW	65 mW

III. Fabrication and Measured Results

The doubler was fabricated on a vapor phase epitaxy (VPE) substrate that had a buried n^+ layer to minimize the diode series resistance [8]. An Au/Ge/Ni/Ag/Au alloy was used for the ohmic contact, and Ti/Pt/Au metallization for Schottky barrier contacts. Si_3N_4 was used for both the capacitor dielectric layer and chip passivation. Following completion of the circuits through the front side, via-holes were etched in the thinned wafer. Gold was then plated onto the back side and via-holes to a thickness of 10 μm prior to dicing the chips. The diodes had a breakdown voltage greater than 16 V.

The doubler was RF tested by mounting the chip to a test fixture consisting of a U-band input and W-band output microstrip to ridged waveguide transitions. The measured output power and efficiency with input power ranging from 15 to 25 dBm are shown in Figure 3. The reverse bias applied to the varactor diode was 7 V. The doubler exhibited a maximum efficiency of 25% (6 dB conversion loss) and output power of 55 mW at an input power of 220 mW. 65 mW output power was obtained at an input level of 330 mW. The predicted output power and efficiency using LIBRA and the nonlinear diode model described in previous section are also shown in the figure and exhibit very good agreement with the measured results.

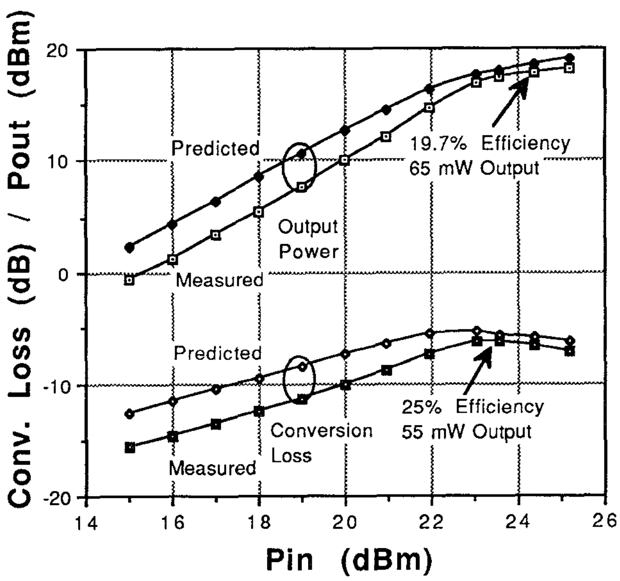


Figure 3. Measured and predicted performance of the doubler

IV. Conclusions

Theoretical analysis and simulated performance of a Schottky barrier varactor diode frequency doubler have been presented. Optimum diode parameters exist for optimum efficiency and output power and can be determined from analysis. A state-of-the-art 94-GHz doubler was designed and fabricated based on the results of the diode analysis and the use of a simple circuit topology. Measured results on the varactor diode and doubler showed excellent agreement with the predicted performance.

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