EXPERIMENTAL MODELING FOR MILLIMETER-WAVE MONOLITHIC INTEGRATED CIRCUIT COMPONENTS

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ABSTRACT

An accurate distributed model of monolithic metal-insulator-metal (MIM) capacitors has been developed for computer-aided design of millimeter-wave monolithic integrated circuits at V-band. It is based on experimental measurements on microstrip ring resonators with and without the air-bridges and capacitors. The model takes into account the effects due to the air-bridge discontinuity, as well as dielectric and ohmic losses. The calculated resonant frequencies are in good agreement with the experiments. This capacitor model reduces discrepancy in the resonant frequency by more than 30% compared with that used in commercially available programs. It provides better correlation with the measured results of a monolithic two-stage low noise HEMT amplifier at V-band.

INTRODUCTION

Millimeter-wave monolithic integrated circuit designs require accurate models of various basic circuit elements. At these frequencies, the lumped elements and discontinuities are comparable to the wavelength. This require accurate distributed models so that the designer can develop millimeter-wave monolithic integrated circuits with a high rate of success.

Air-bridges and Metal-Insulator-Metal (MIM) capacitors are frequently utilized in monolithic microwave and millimeter-wave integrated circuits. Air-bridges are used in the realization of spiral inductors and capacitors. MIM capacitors are used as a blocking or bypass elements. The RF performance of the capacitor significantly determines the overall performance of the circuits. Some approximate models for the capacitors are available at microwave frequencies [1],[2]. The circuit designs at millimeter-wave frequencies utilizing them lead to inaccurate simulations of their performance. To the authors' knowledge, there are no published models of air-bridges and capacitors which could be used with confidence at these frequencies. To that end we have developed accurate models of air-bridge and capacitor. The capacitor model takes into account the effects due to an air-bridge discontinuity, as well as dielectric and ohmic losses.

In this paper, we present experimental and theoretical aspects leading to the development of the air-bridge and capacitor model. We also compare measured results with the computer simulation of a V-band two-stage low-noise amplifier using the capacitor model.

EXPERIMENTS WITH MICROSTRIP RESONANT RINGS

In developing the circuit models for the air-bridge and MIM capacitor at millimeter-wave frequencies, we have evaluated these discontinuities in a microstrip resonant ring. The ring resonates whenever its electrical length is an integral multiple of the guide wavelength. The rings were designed with a mean diameter of 0.5035 mm and width of 0.072 mm on a 0.1 mm thick GaAs substrate.

Figure 1 summarizes experimental and calculated results for microstrip ring resonator without any discontinuity as well as with air-bridges and MIM capacitors. The measured resonant frequency for the microstrip ring resonators is 64.3 GHz, while the calculated value is 64.5 GHz obtained using an accurate value of the effective dielectric constant [3]. The agreement is within 0.3 percent.

The air-bridge is modeled as a microstrip transmission line on a layered dielectric substrate. Using equivalent dielectric constant of the layered medium, the calculated resonant frequency is 64.9 GHz. This is within 0.3 percent of the measured frequency 64.7 GHz.

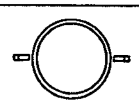
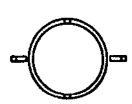
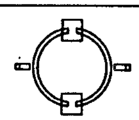
MICROSTRIP RINGS	RESONANT FREQUENCY		
	MEASURED (GHz)	CALCULATED (GHz)	% DIFFERENCE
	64.3	64.5	0.3
 WITH AIR BRIDGES	64.7	64.9	0.3
 WITH MIM CAPACITORS	55.0	55.2	0.4

Fig. 1 Experiments with microstrip ring resonators. (a) without discontinuity. (b) with air-bridge. (c) with MIM capacitor.

In the model of MIM capacitor, the effect of the GaAs substrate between the bottom capacitor plate and the ground plane is modeled as a transmission line, and the dielectric between the plates is considered part of the parallel plate capacitor. The transmission line is modeled using the accurate expressions [3]. Using our model, the calculated resonant frequency is 55.2 GHz. This is within 0.4 percent of the measured value of 55.0 GHz. It is interesting to point out that the thin-film-capacitor model in a commercially available software program [5] produced an error of about 32 percent in the resonant frequency.

AIR-BRIDGE MODEL

As mentioned earlier, the air-bridge section is modeled as a microstrip transmission line with an equivalent dielectric constant of a bilayered dielectric substrate, as shown in Fig. 2. A simple expression of the equivalent dielectric constant is given by

$$\varepsilon_{eq} = \frac{(d_a+d_s)\varepsilon_a \varepsilon_s}{\varepsilon_a d_s + \varepsilon_s d_a} \tag{1}$$

where ε_a and ε_s are the dielectric constants of the layered substrates of thickness d_a and d_s , respectively. This expression along with accurate closed form equations for microstrip transmission line given in [3] are utilized in the model.

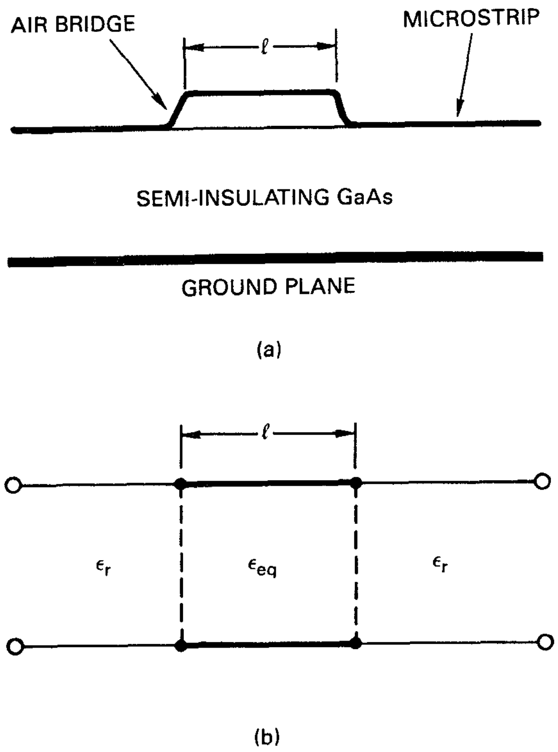


Fig. 2 (a) side view, and (b) transmission line equivalent circuit of an air-bridge. ε_{eq} is the equivalent dielectric constant.

MIM CAPACITOR MODEL

The model for the MIM capacitor is shown in Fig. 3. The parallel plate capacitance, C_p, is given by,

$$C_p = \varepsilon_o \varepsilon_r W_c \frac{l_c}{d_s} \tag{2}$$

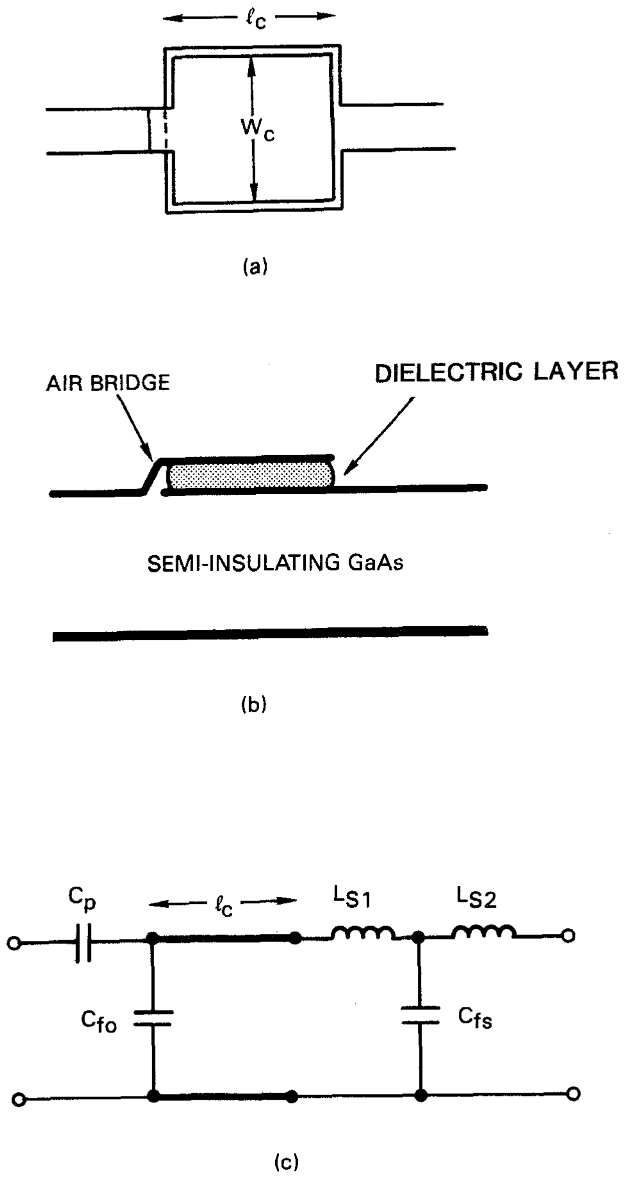


Fig. 3 (a) top view, (b) side view, and (c) equivalent circuit of a MIM capacitor. C_p is the parallel plate capacitance, C_{fo} and C_{fs} are fringing capacitances, and W_c and l_c are the width and length of the capacitor, respectively.

The capacitor model proposed in this paper includes fringing capacitance C_{fo} from bottom plate to the ground. We model the open end fringing capacitance as,

$$C_{fo} = \frac{1}{\omega Z_{oc}}\left(1-\frac{W_s}{W_c}\right)\tan\beta l_{eo} \tag{3}$$

where W_s and W_c are the widths of the microstrip line and capacitor plate, respectively. Z_{oc} is the characteristic impedance corresponding to microstrip line of width W_c and β is the wave number in the dielectric medium at angular frequency ω. The expression for open-end effective length used in the model is [4]

$$l_{eo} = 0.412\, d_s\, \frac{(\varepsilon_{eff}+0.3)}{(\varepsilon_{eff}-0.258)} \frac{\left(\frac{W_c}{d_s}+0.262\right)}{\left(\frac{W_c}{d_s}+0.813\right)} \tag{4}$$

where ε_{eff} is the frequency dependent value of the effective dielectric constant. L_{s1}, L_{s2}, and C_{fs} are inductances and capacitances associated with the microstrip step change in width. They are given as follows [4]:

$$L_{s1} = \frac{L_{Ws}}{L_{Ws}+L_{Wc}} L_s \tag{5}$$

$$L_{s2} = \frac{L_{Wc}}{L_{Ws}+L_{Wc}} L_s \tag{6}$$

where

$$\frac{L_s}{d_s} = 40.5\left(\frac{W_s}{W_c}-1.0\right) - 75\log\frac{W_s}{W_c} + 0.2\left(\frac{W_s}{W_c}-1.0\right)^2 \tag{7}$$

and

$$\frac{C_{fs}}{\sqrt{W_s W_c}} = 130\log\left(\frac{W_s}{W_c}\right) - 44 \tag{8}$$

Using the above equations, we have calculated the insertion loss and return loss in Figs. 4 and 5, respectively, and compared with the reference data available in the literature. It is observed that our model predicts slightly lower insertion loss and reasonable return loss characteristics.

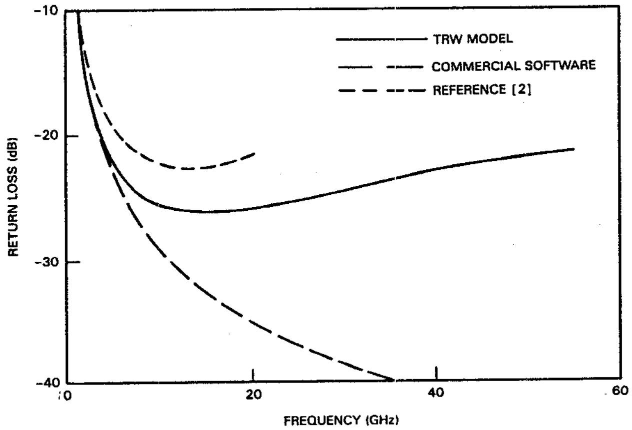
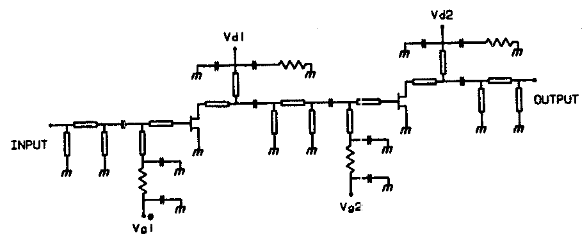


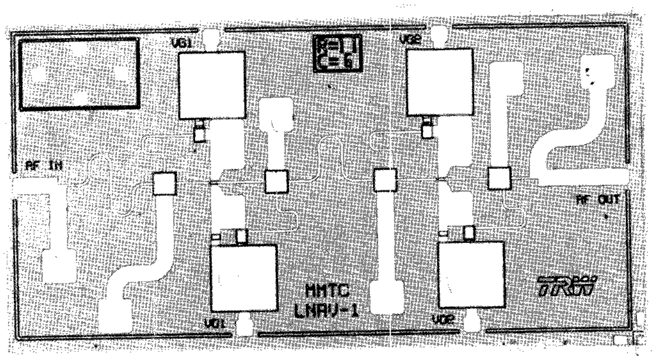
Fig. 5 Comparison of calculated return loss of a MIM capacitor.

EXPERIMENTAL VERIFICATION OF THE MODELS

The distributed model of the MIM capacitor is utilized in the simulation of the performance of a V-band two stage low noise amplifier. The schematic circuit diagram and the photograph of the chip are shown in Fig. 6. In this circuit, the



(a)



(b)

Fig. 6 V-band monolithic low noise amplifier. (a) schematic diagram. (b) completed chip.

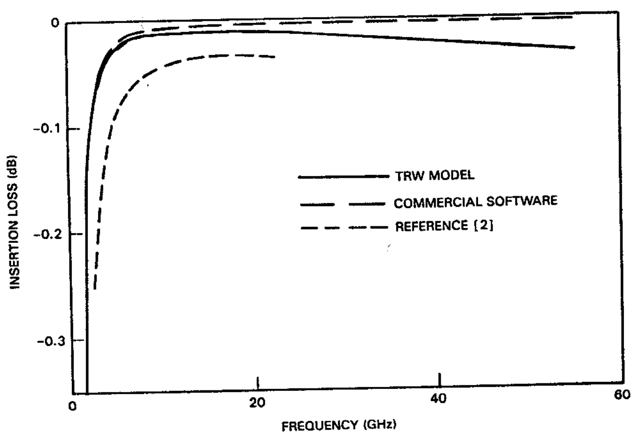


Fig. 4 Comparison of calculated insertion loss of a MIM capacitor.

RF blocking capacitors (1.36 pF) are realized by 87 μm × 87 μm plates separated by 0.26 μm, and the RF bypass capacitors (0.32 pF) are realized by 50 μm × 36 μm plates separated by 0.26 μm. The dielectric constant of the material is 3.9. Also, the amplifier circuit is simulated using the MIM capacitor model of the commercially available software program [5]. Fig. 7 shows the gain of the amplifier from 55 to 65 GHz using above simulations along with measured results. It is seen that the performance predicted using our model provides good correlation with the measured performance.

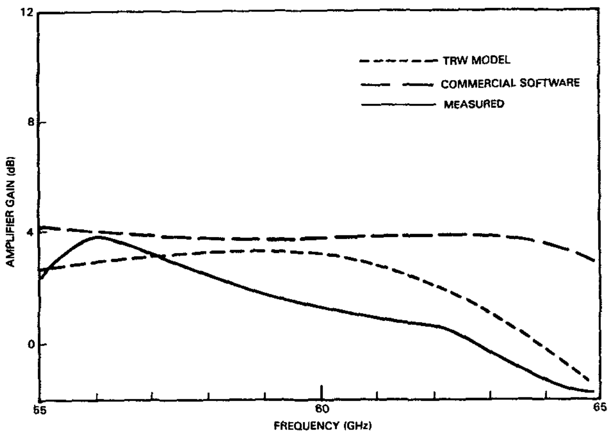


Fig. 7 Comparison of measured and calculated amplifier gain.

CONCLUSION

In this paper we have described an accurate distributed model of a MIM capacitor. This model takes into account the effects due to air-bridge discontinuity, and dielectric and ohmic losses. We have found that computer simulations obtained using this model are in good agreement with the experiments. This demonstrates the applicability of our model in millimeter-wave monolithic integrated circuit components.

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