Eigenmode Analysis of Propagation Constant for a Transmission Line with Dummy Metals on a Si CMOS Substrate

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1. Introduction

Millimeter-wave CMOS RF circuits have been received substantial attention in recent years, motivated by the advancement of CMOS process. The RF circuit consists of several metal layers and vias. The metal filling rate must be satisfied, usually 25% to 75% to satisfy design rules in the semiconductor process, especially chemical mechanical polishing (CMP) rule. Because of CMP rule, dummy metals with 2 um up to 10 um square are necessary all over the chip. The influence of dummy metals is not negligible in millimeter-wave band though it has been ignored below the frequency range of a few GHz [1]. In this study, the propagation constant of a guided microstrip line on a Si CMOS substrate is analyzed by the eigenvalue analysis for one period of the line, which is considered as a periodic structure [2][3]. The calculated propagation constant is compared with the measurement of a chip fabricated by the CMOS 0.18um process.

2. Guided Microstrip Line on a Si CMOS Substrate

A transmission line, a guided microstrip line, on a Si CMOS substrate with dummy metals is shown in Fig. 1. The transmission line consists of several metal layers and vias which connect them. Because of CMP rule, dummy metals with 2 um up to 10 um square are necessary all over the chip in the CMOS 65 nm or later process. SiO_2 is used as insulator between metal layers. The ground plane and signal line are realized by the bottom and top metal, respectively. There are metal walls, or a guide, on both sides of the signal line which consists of metal layers and vias. Distance from the guide to the signal line is enough so that the guide does not affect transmission characteristic of the microstrip mode. Dummy metals and vias, which are small compared with a wavelength, are arranged periodically.

3 . Calculation Method of the Propagation Constant [2][3]

The propagation constant is calculated as followings.

(1) Extract unit cell and its analysis model

A period of the structure, usually the smallest period of transmission line, is referred to as a unit cell. A unit cell is modelled as shown in Fig. 2. Because of the symmetry of the structure and excitation, the analysis model can be reduced to a half of full structure with perfect magnetic conductor (PMC) wall on the symmetrical plane. Periodic boundary condition is used on two walls of the structure.

(2) Phase constant

The periodic boundary walls have phase difference ψ, Floquet mode, in order to simulate phase delay of the propagating wave. The phase constant can be calculated as $\beta = -\psi / s$, where s is the length of a period. The top and side walls are absorbing boundary condition, or radiation boundary. The Si substrate is not modelled in the simulation, and guides are modelled by metal blocks in the simulation.

(3) Attenuation constant

The unit cell in Fig. 2 is considered to be a cavity resonator. The complex resonant frequency of the cavity resonator can be analyzed by solving the eigenvalue problem. In the analysis, the 3-D FEM based simulator Ansoft HFSS is used in this paper. The dispersion curve of the phase constant β is obtained from real part $\omega = \mathrm{Re}[\omega_c]$ of the complex resonance angular frequency ω_c and the phase constant β in (2). Q factor $Q = |\mathrm{Re}[\omega_c]/(2\,\mathrm{Im}[\omega_c])|$ can be obtained from ω_c. The attenuation constant can be calculated as $\alpha = \omega(\partial\beta/\partial\omega)/(2Q)$ [4].

4. Results

The propagation constant of the transmission line in Fig. 1 was analyzed and measured. Figure 3 shows the electric field of the eigenmode for a guided microstrip line with dummy metals. Microstrip mode is observed. Figure 4 shows the micrograph of a fabricated chip (CMOS 0.18um, 2.5mm square). Figure 5 shows frequency characteristic of the propagation constant. Figure 5 (a) shows attenuation constant, loss per 1 mm, of the transmission line. The loss is calculated as $20\log_{10} e^{-0.001\alpha}$ [dB/mm] with the attenuation constant α [Np/m]. Solid and broken lines are results without and with dummy metals, respectively. The lines with Exp and Cal are results by measurement and calculation explained in the previous section, respectively. The Thru-Reflect-Line (TRL) calibration was used for de-embedding of pads in the measurement. At 60 GHz the calculated losses without and with dummy metals are 0.88 dB/mm and 1.1 dB/mm, respectively. The measured losses without and with dummy metals are 0.93 dB/mm and 1.15 dB/mm, respectively. The tendency of frequency characteristic agrees very well between calculation and measurement. The influence of dummy metals is small in low frequency regions, while it is not negligible in millimetre-wave band. Figure 5 (b) shows frequency characteristic of the phase constant. Calculated values agree very well with the measured one. The phase constant of the transmission line with dummy metals becomes larger than that without dummy metals because dummy metals acts as an artificial dielectric.

5. Conclusion

The propagation constant of a guided microstrip line on a Si CMOS substrate is analyzed by the eigenvalue analysis. The calculated propagation constant is compared with measurement fabricated by the CMOS 0.18um process. At 60 GHz the calculated losses without and with dummy metals are 0.88 dB/mm and 1.1 dB/mm, respectively. The measured losses without and with dummy metals are 0.93 dB/mm and 1.15 dB/mm, respectively. The tendency of frequency characteristic agrees very well between calculation and measurement.

Acknowledgments

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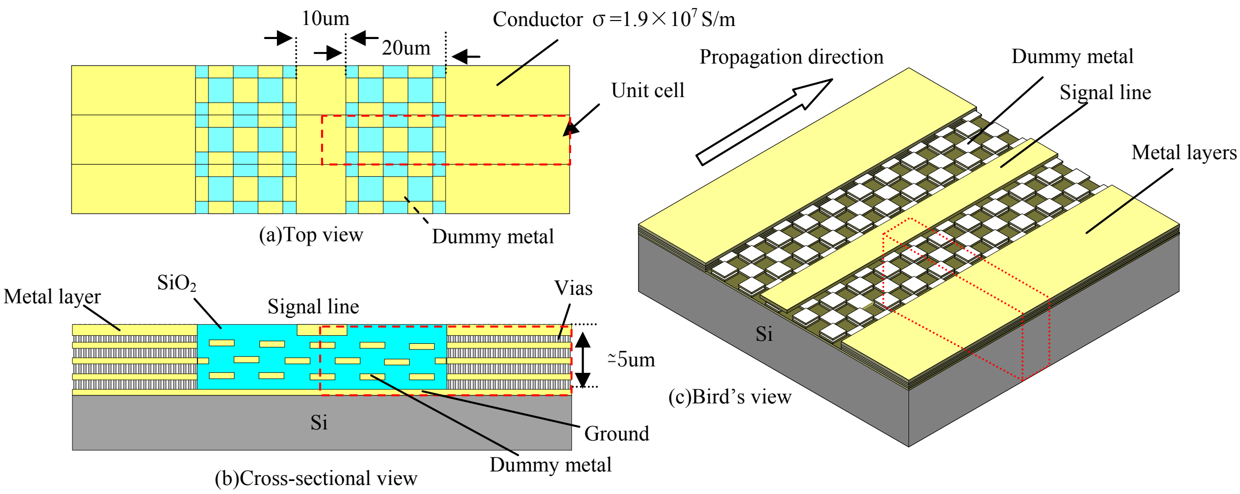


Figure1: Guided microstrip line on a Si CMOS substrate

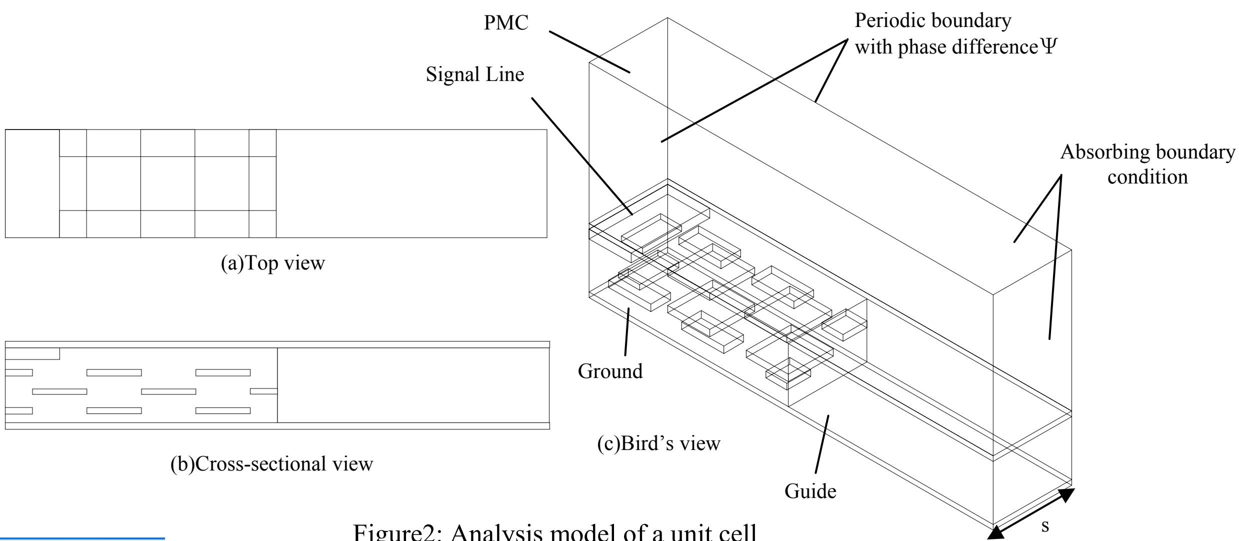


Figure2: Analysis model of a unit cell

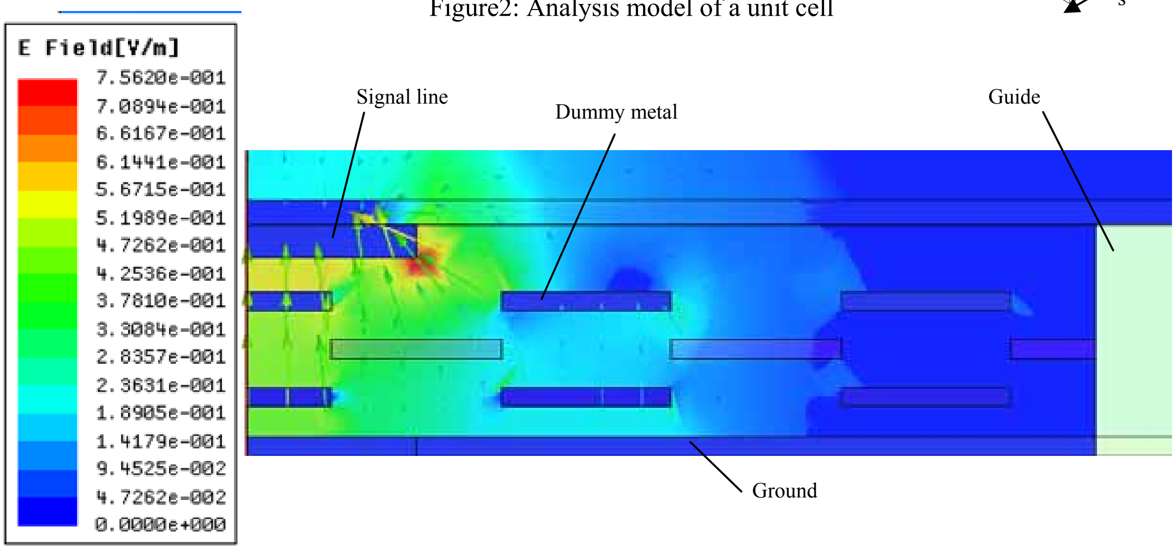


Figure3: Electric field of the eigenmode for a guided microstrip line with dummy metals

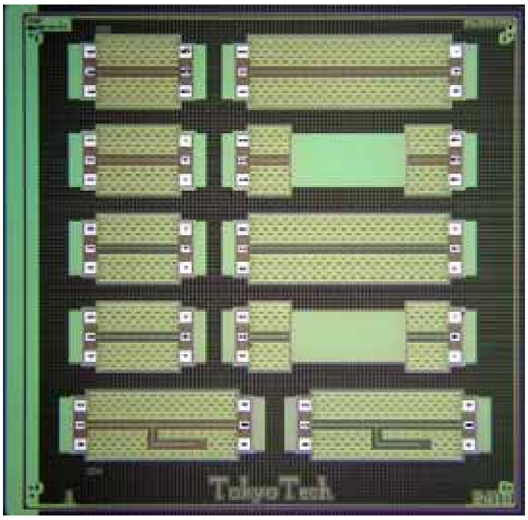
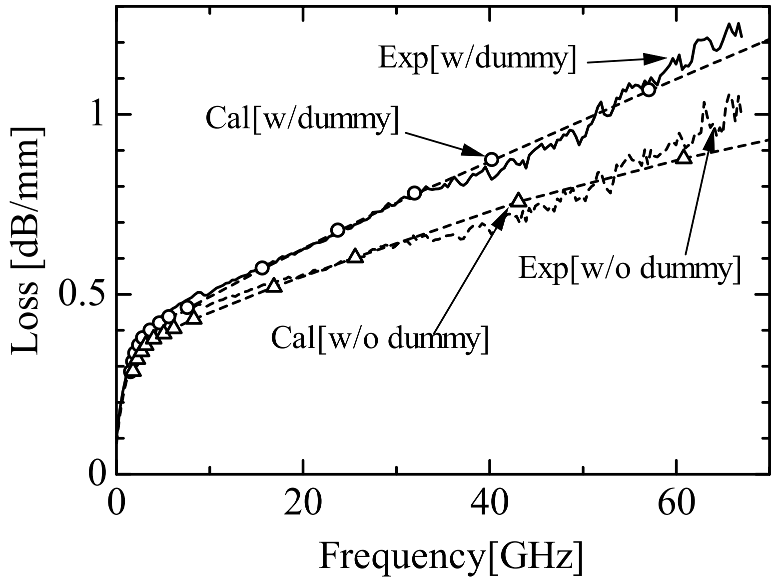
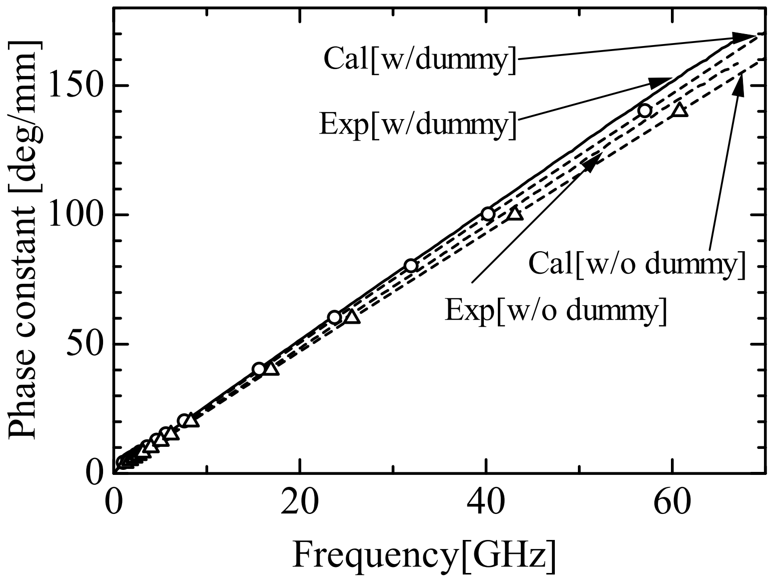


Figure 4: Micrograph of the chip (CMOS 0.18um, 2.5mm square)



(a) Attenuation constant



(b) Phase constant

Fig.5 Frequency characteristic of propagation constant