

Characterization of low impedance 3d coplanar waveguide interconnects for compact MMICs

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Abstract. Low characteristic impedance coplanar waveguide (CPW) interconnects are desirable for microwave applications such as power FET's and photodiodes. In conventional planar MMICs, typical characteristic impedances are in the range of 40-100 Ω , such that in order to realize 20 Ω interconnect, one has to fabricate a very narrow slot width with a wider signal conductor width. As the objective is to achieve low characteristic impedance interconnects (<20 Ω), the proposed techniques are by employing an additional metal layer to increase the intrinsic distributed capacitance within interconnect. In this work, realization of low impedance 3D CPW interconnect has been done by employing the overlapped metal techniques. The microwave characteristics are studied with different signal conductor widths and it has shown that the characteristic impedance as low as 10 Ω can be achieved for MMIC interconnects with slot width of 15 μm . This illustrates the great flexibility of the multilayer technology allowing various parameters to be achieved with small modifications in the design structure.

1. Introduction

Since the requirement of having more compact MMICs, by increasing the packing density and functionality of chips become stronger, the conventional planar CPW interconnects are not suitable to realize the desired low characteristic impedance interconnects. The solution would be to employ the 3D multilayer interconnects technique [2]. Gillick and Robertson [1] demonstrated that CPW structure with $Z_0 = 9\Omega$ and loss of 0.2dB/mm can be achieved at 10 GHz. Vo et al [2] also demonstrated using another design approach to yield low loss low impedance transmission line. However there is still much information which can be extracted from the comparison based on the CPWs' various design parameters [1,2] and various metal overlapped dimension (between signal conductor tracks in different layer positions with the ground planes). Detailed investigation such as verifications of the extracted parameters using S-parameter measurements in any published data is also necessary to be carried-out. These are presented in this paper. We demonstrate that the losses can be reduced significantly by utilizing additional metal layer with different gap sizes. These have been analyzed by extracting various multilayer interconnects' characteristics with respect to the overlapped metals width.



2. Interconnect Characterization

An interconnect is a distributed physical system which conveys a communication signal and transmits bulk power over a particular distance. Due to its important characteristics, many researches have been devoted to develop various types of CPW interconnect for microwave and millimetre-wave integrated circuits [5-9]. Numerous researches have been dedicated to understand the electrical behavior of this structure, especially at microwave frequencies [7,9,10]. However, most of these studies have been performed using analytical approximation and full-wave analysis [10,11]. Therefore, it is essential to obtain results using S-parameters characterization technique especially for 3D CPW MMIC interconnects. Interconnect's signal transmission is defined using the classical Telegrapher's transmission line equation [12-15]. The S-parameter responses from a lossy unmatched transmission line can be derived from the ABCD parameters of the particular transmission line where terminal conditions are implemented at the two ends of the line [13,14].

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_0 \sinh(\gamma l) \\ \frac{\sinh(\gamma l)}{Z_0} & \cosh(\gamma l) \end{bmatrix} \quad (1)$$

The matrix above is defined as transfer matrix of the transmission line with length l and γ is the complex propagation constant of the signal travelling in transmission line. The ABCD parameters relate the voltage and current of one port namely load to the voltage and current of the other port namely source. Then, characteristic impedance of transmission line l can be expressed in S-parameters by converting the parameters above. Since $B=Z_0 \sinh(\gamma l)$ and $C=\sinh(\gamma l)/Z_0$, one can convert these parameters into S-parameters as follow:

$$Z_0 \sinh(\gamma l) = Z_{\text{sys}} \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}} \quad (2)$$

and

$$\frac{\sinh(\gamma l)}{Z_0} = \frac{1}{Z_{\text{sys}}} \frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}} \quad (3)$$

where $S_{11}=S_{22}$ and $S_{12}=S_{21}$ due to symmetrical interconnect. Simplify and combine equation (2) → (3) one can yield

$$Z_0^2 = Z_{\text{sys}}^2 \frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2} \quad (4)$$

In order to express relative effective permittivity formula of particular transmission line in terms of S-parameters, one has to derive the complex propagation constant (γ) equation from the simulated or measured of S-parameters. By converting A parameter to S-parameters and combining B to C parameters equations with terminal conditions of transmission line [14] we can have

$$A = \cosh(\gamma l) = \frac{(1+S_{11}-S_{22}-\Delta s)}{2S_{21}} \quad (5)$$

where

$$\begin{aligned} S_{11} &= S_{22}, S_{12} = S_{21} \\ \Delta s &= S_{11}S_{22} - S_{21}S_{12} \end{aligned} \quad (6)$$

Then

$$\cosh(\gamma l) = \frac{(1 - S_{11}^2 + S_{21}^2)}{2S_{21}}. \quad (7)$$

Also by combining equation (2) $\rightarrow$ (3) where

$$\sinh(\gamma l) = \frac{Z_{\text{sys}}}{Z_0} \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (8)$$

and

$$\frac{Z_{\text{sys}}}{Z_0} = \frac{1}{\sinh(\gamma l)} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (9)$$

Thus, one can yield

$$\sinh^2(\gamma l) = \frac{((1 - S_{11})(1 - S_{22}) - S_{12}S_{21})((1 + S_{11})(1 + S_{22}) - S_{12}S_{21})}{(2S_{21})^2}.$$

then,

$$\sinh(\gamma l) = \left\{ \frac{(S_{11}^2 - S_{21}^2 + 1)^2 - (2S_{11})^2}{(2S_{21})^2} \right\}^{\frac{1}{2}} \quad (10)$$

Therefore, the equation of propagation constant of transmission line with length l in term of S-parameters can be expressed by adding or subtracting both equations (7) and (10) as follow

$$\cosh(\gamma l) \pm \sinh(\gamma l) = e^{(-\gamma l)} = \left\{ \frac{(1 - S_{11}^2 + S_{21}^2)}{2S_{21}} \pm K \right\} \quad (11)$$

where

$$K = \sinh(\gamma l) = \left\{ \frac{(S_{11}^2 - S_{21}^2 + 1)^2 - (2S_{11})^2}{(2S_{21})^2} \right\}^{\frac{1}{2}}$$

After acquiring the value of $\beta = \text{imag}(\gamma)$ from S-parameters of measured or simulated structure then we can express the effective dielectric constant based on its S-parameter using equation

$$\epsilon_{r, \text{effective}} = \left(\frac{\beta c}{2\pi f} \right)^2 \quad (12)$$

The common approach to plot the variation of interconnects' dissipation loss is to consider the two-port network principle where the output power and the transmitted power can be approximated as $|S_{21}|^2$ and $1 - |S_{11}|^2$ respectively. Then the dissipation loss can be expressed by [2]

$$\text{Dissipation_Loss} = 10 \log \left(\frac{1 - |S_{11}|^2}{|S_{21}|^2} \right) \quad (13)$$

We have used this procedure to determine various parameters of the transmission lines studied.

3. Experimental Details And Results

Several 3D multilayer interconnects have been designed, fabricated and tested. Semi-insulating GaAs substrate with a $600\mu\text{m}$ thickness has been used to fabricate the structures using photolithographic technique. The conducting electrodes were Ti($0.05\mu\text{m}$) and Au($0.8\mu\text{m}$). The thickness of isolating polyimide layers were $2.5\mu\text{m}$ with dielectric constant approximately 3.7. Agilent's ADS Momentum was used for electromagnetic modeling and the fabricated interconnects were characterized at microwave frequencies using a Cascade Microtech probe station and HP8510C vector network analyzer.

The structure that has been considered to verify the characterization of the two different approaches is shown in figure 1. As for realizing the low impedance interconnects, structures in figure 2 were modeled, fabricated and tested with various signal conductors (W), gap (G) and different overlap (O) widths. The results in figure 3 show that a good agreement has been achieved between the simulated and modeled 3D interconnection term of effective dielectric constant and the characteristic impedance. For dispersion characteristics and dissipation loss analysis, we modeled and measured structure as shown in figure 2.

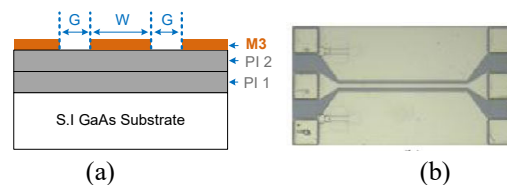


Figure 1. (a) Cross-sectional view and (b) micrograph of fabricated multilayer interconnect with polyimide thickness $3\mu\text{m}$, length of 0.5 mm and $W=20\mu\text{m}$, $G=15\mu\text{m}$

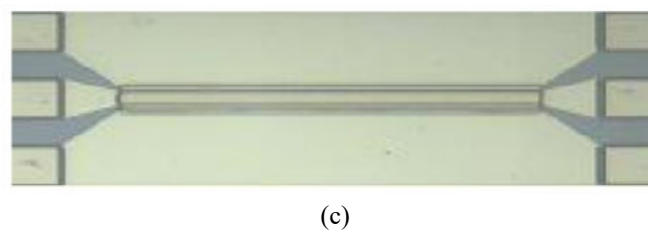
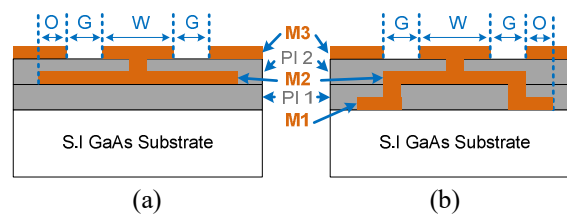


Figure 2. Cross-sectional view of (a) overlap M23 (b) overlap M123 interconnects and (c) the micrograph of fabricated overlap metal interconnect with polyimide thickness of $5\text{-}\mu\text{m}$, length of 2.398mm

The interconnects with two overlapped metal layers are examined with different signal conductor and overlap widths. The lengths for all the structures are kept constant at 2.398mm . The dispersion characteristics and the dissipation loss are shown in figures 4a and 4b respectively. The dispersion showed that as the overlap width between metal 2 and 3 increases by 10 times then the characteristic impedance decreases on average by about 37%. As the overlap increases further by 20 times the characteristic impedance decreases on average by about 52%. The reduction of the Z_0 is mainly due to the increased capacitance to the ground of the structure. This argument can be validated by observing the trends of effective dielectric constant in figure 4a.

The effective dielectric constant is the ratio of total capacitance per unit length of the coplanar line with the capacitance of the same line while all the dielectrics replaced by air [11]. Since the capacitance with air as the dielectric does not change but at the same time the total capacitance of the line increases thus the effective dielectric constant increases. Utilizing the common approach used in designing conventional planar interconnect i.e. by increasing the signal conductor width does not decrease the characteristic impedance significantly since the capacitance only increases slightly. It also does not give benefit in decreasing the dissipation loss.

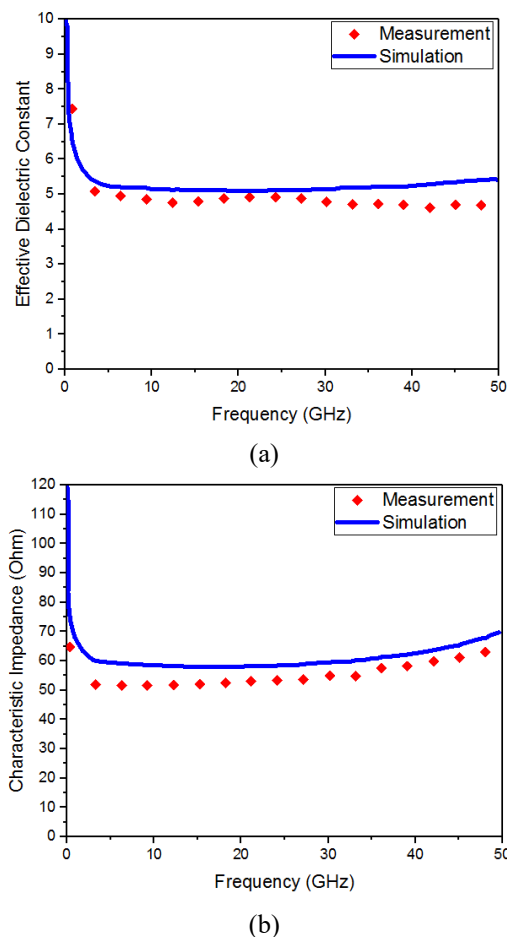


Figure 3. Comparison data of (a) effective dielectric constant and (b) characteristic impedance of the multilayer M3 PI12 transmission line with length 0.5mm

Wider signal conductor width only reduces the dissipation loss by 0.05dB/mm. Significant reduced characteristic impedance can be achieved by increasing the overlap width i.e. increasing the width of metal 2 in figure 2a. However it also increases the dissipation loss of the structure by 0.1–0.6dB/mm. Since the objective is to achieve low loss low characteristic impedance interconnect then reducing the dissipation loss can be performed easily in the multilayer structure by employing an additional metal layer and using a wider gap size i.e. reducing ground width as shown in figure 2b. These results in lowering the dielectric losses due to reduced electric field at the overlapping area and also more dispersed current in the conductor leads to reduce the current crowding effect. Using this design approach, the dissipation loss decreases by 0.6dB/mm for structure with the same overlap width. The experimental data showed that the two overlapped metal layers technique is more sensitive to losses while the three overlapped metal layers with different gap size has lower dissipation loss by 0.26dB/mm for the same characteristic impedance value. This illustrates the great flexibility of the

multilayer technology allowing various parameters to be achieved with only small modifications to the design structure.

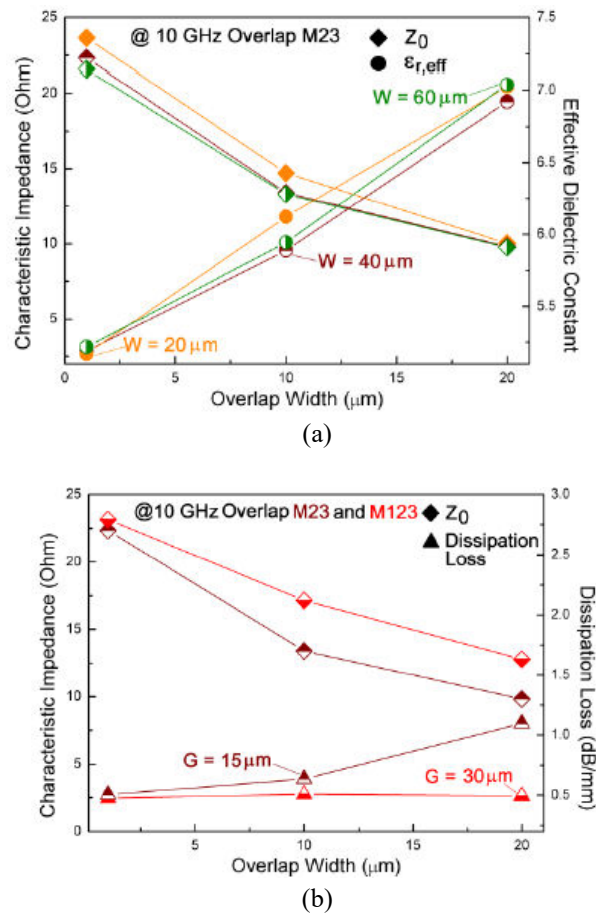


Figure 4. (a) Characteristic impedance and effective dielectric constant (b) dissipation loss and total power loss of overlap M23 transmission line $G=15\mu\text{m}$ with various width W , (c) characteristic impedance and dissipation loss of overlap M23, $W=40\mu\text{m}$, $G=15\mu\text{m}$ and overlap M123, $W=40\mu\text{m}$, and $G=30\mu\text{m}$

4. Conclusions

Good agreement between the measured S-parameter data and those obtained from the analytical results validates the characterization of 3D CPW interconnects based on S-parameters extraction technique. By utilizing the 3D multilayer CPW technique, low impedance interconnects with improved dissipation loss can easily be realized without increasing the size of the components in compact MMICs. The trend of dispersion characteristics show that this technique gives microwave engineers more flexibility in designing passive components with improved performances.

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