

Dielectric Propagation Extraction of Coplanar Waveguide with Air Pocket by Conformal Mapping

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Abstract - This paper proposes a new technique for extracting the dielectric permittivity and loss of materials using coplanar waveguides (CPWs) with air pockets. A set of CPWs with varying depths of air slots is used to extract the loss behavior relative to slot depth, based on conformal mapping. Theoretical foundations of the technique were developed, and simulation and experimental verification was carried out, resulting in very low error rates. Specifically, the model was verified with materials with permittivity ranging from 3.1-30 and loss tangents from 0.01-0.06. The technique was also experimentally confirmed using traditionally-manufactured FR-4 dielectrics up to 10 GHz. Results showed an average error of only 2% across the studied cases.

I. INTRODUCTION

A novel conformal mapping-based characterization technique using coplanar waveguides (CPW) with air pockets that allows for dielectric permittivity and dielectric loss extraction (1). Picosecond Nd:YAG laser is used to machine slots in a 20-25- μm -thick layer of silver paste (Dupont CB028) that is micro dispensed on a Rogers RT5870 substrate, producing coplanar waveguide (CPW) transmission lines with 16- 20 μm -wide slots (2). Meshed ground coplanar waveguide (MGCPW) is analyzed by simulating, fabricating and measuring a broad set of meshed ground geometry sizes (3). Laser-enhanced direct print additive manufacturing (LE-DPAM) is used to fabricate capacitors and inductors for coplanar waveguide (CPW) circuits (4). Micro dispensed dielectric pastes are suitable for such an application and a microwave characterization process is described in (5). The extraction of magnetically tuned 3-D printed materials suitable for RF circuits is mentioned in (6). Characterization methods are presented with results from test structures printed with varying printing parameters and materials is mentioned in (7). The integration of 3D and inkjet printing manufacturing processes with millimeter-wave (mm-wave) wireless packaging technology is described in (8). A wide variety of materials over a broad spectrum of frequencies from 1 MHz to 10 GHz using a variety of well-established measurement methods are described in (9). Direct application of these antennas for free space dielectric material characterization is mentioned in (10). A transmission line method for measuring the complex permittivity of dielectric

materials using propagation constant measurements is explained in (11). Methodology for extracting high-frequency IC interconnect transmission parameters directly from S-parameter measurements has been demonstrated using on-chip test structures. (12). A tunable rectangular cavity to operate in TE₁₀₃ mode was designed and fabricated. (13).

II. ANALYSIS OF COPLANAR WAVEGUIDES WITH AIR POCKET SLOTS

An air pocket in a coplanar waveguide (CPW) refers to the presence of air, or any low-loss dielectric material, in the region between the signal conductor and the ground plane. This air pocket can be intentionally created in the CPW structure to achieve certain desired electrical properties. The presence of an air pocket in the CPW structure can help reduce the dielectric loss, which is a common issue in conventional CPW structures.

To create an air pocket in the CPW structure, a trench is typically etched into the substrate below the signal conductor and between the ground planes. The air pocket is then formed when the upper surface of the trench is covered by the signal conductor. One potential issue with creating an air pocket in the CPW structure is that it may affect the mechanical stability of the structure. The analysis of coplanar waveguide (CPW) with air pocket slots typically involves several steps, including the calculation of the electromagnetic field distributions, the determination of the equivalent circuit model, and the computation of the insertion loss, characteristic impedance, and electrical parameters.

An approach to analyzing CPW with air pocket slots is to use an analytic or semi-analytic method, such as the conformal mapping technique. This method involves modelling of the CPW structure as a conformal map or using Fourier analysis to solve the Maxwell's equations and obtain the electrical parameters.

In summary, the analysis of coplanar waveguide with air pocket slots involves the calculation of electromagnetic field distributions, the determination of the equivalent circuit model, and the computation of electrical parameters. Numerical and analytic methods can be used for this purpose depending on the complexity and accuracy requirements of CPW structure.

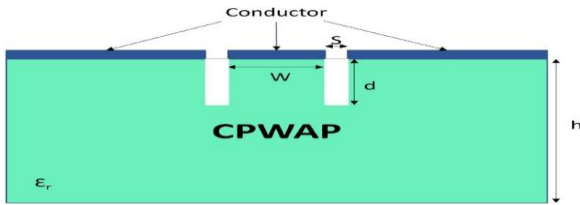


FIG-1 (Coplanar waveguide with air pocket slots)

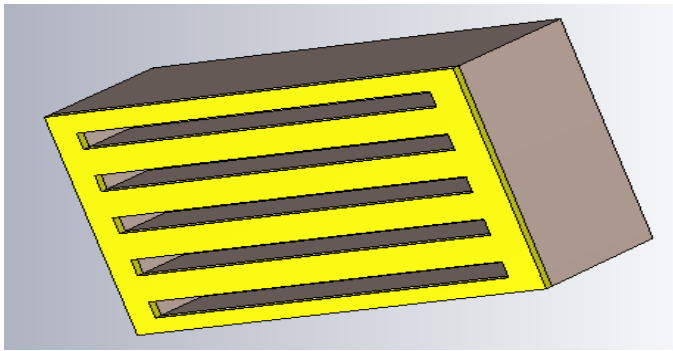


FIG-2 (3-D diagram of Coplanar waveguide with air pocket slots geometry and dimension)

III. MATHEMATICAL ANALYSIS OF CPW

A. Comprehensive approach and Configuration:

The propagation characteristics of a coplanar waveguide with non-magnetic Substrates can be fully described by its effective electric permittivity. The equations for characteristic impedance and dielectric loss are given below that is dependent upon the effective permittivity of the structure. Where,

$$\text{Characteristic impedance } (z_0) = \frac{1}{c \sqrt{\epsilon_{eff}} C_a} \quad (1)$$

And

$$\text{dielectric loss } (\alpha_d) = \frac{\pi}{\lambda_0} \frac{\epsilon_r}{\sqrt{\epsilon_{eff}}} \frac{\epsilon_{eff}-1}{\epsilon_r-1} \quad (2)$$

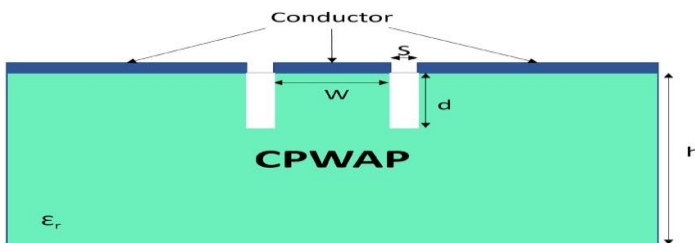


Fig -3. (Coplanar waveguide with air pocket slots)

In coplanar waveguide substrate,

C = speed of light in vacuum

ϵ = effective permittivity of travelling wave

C_a = capacitance per unit length in vacuum

α_d = attenuation constant

λ_0 = free – space wavelength

ϵ_r = relative permittivity

$\tan \delta$ = loss tangent

By using CPW-AP with air pocket slots of varying sizes, we can determine the dielectric loss tangent's contribution to the overall CPW-AP loss and extract its loss tangent. Adding d , the depth of the slot, to the typical CPW geometry parameters of W , S , and h , we can fully understand the structure's propagation characteristics. The following study focuses on the effect of the slot depth on effective permittivity, without considering conductor losses.

B. Partial capacitance approximation of cpw-ap slots :

To compute the partial capacitance approximation (PCA) traditional CPWs, the CPW geometry is usually converted into a parallel-plate configuration. This enables the modelling of the capacitance per unit length of the structure using a technique called Schwarz-Christoffel (SC) mapping.

The PCA method is used to estimate the capacitance per unit length of traditional CPW-AP by transforming their geometry into a parallel- plate configuration. This method helps in predicting the effective permittivity and hence determining the propagation characteristics of the CPW-APs. The effective permittivity of a CPW-AP structure depends on the dielectric properties of its constituent materials, including the air pockets, substrate, and conductor. It helps optimizing the design and performance of CPW-AP structures for application like microwave and microwave circuits.

Once the CPW-AP geometry is transformed into a parallel-plate configuration to calculate the PCA, the resulting capacitor structure is no longer a homogeneous dielectric medium, and the capacitance calculation is not straightforward. Additionally, finding the vertices of the mapped structure requires numerical analysis. Hence, the conformal map obtained directly from the CPW-AP geometry does not result in field lines that follow the traditional parallel plate field distribution. When we split the CPW into three different regions, we analyze a multilayer structure.

To calculate the total capacitance of the multilayer CPW,

$$C_{cpw} = 2C_1 + 2C_2 - C_{slot} \quad (3)$$

Where,

C_1 = capacitance in air

C_2 = capacitance in dielectric $\epsilon_r - 1$

C_{slot} = slot capacitance with permittivity ϵ_r

The above capacitances can be derived by using the formulas which are given below:-

$$\epsilon_{r, \text{slot}} = \epsilon_r \sqrt{\epsilon_r} \quad (4)$$

$$C_1 = 2\epsilon_0 \frac{k(k_1)}{k(k'_1)} \quad (5)$$

$$C_2 = 2(\epsilon_r - 1)\epsilon_0 \frac{k(k_2)}{k(k'_2)} \quad (6)$$

$$\text{and } C_{slot} = 2(\epsilon_r - \sqrt{\epsilon_r})\epsilon_0 \frac{k(k_5)}{k(k'_5)} \quad (7)$$

The above equations are calculated by putting these values such as :-

$$k_1 = a/b \quad (8a)$$

$$k_2 = \sinh\left(\frac{\pi a}{2h}\right) / \sinh\left(\frac{\pi b}{2h}\right) \quad (8b)$$

$$k_s = \sinh\left(\frac{\pi a}{2d}\right) / \sinh\left(\frac{\pi b}{2d}\right) \quad (8c)$$

We can put the value of $a/b = W/(W+2S)$, which is known as the aspect ratio of the CPW.

h = height of dielectric substrate

$K(k_i)$ = complete elliptical integral

The value of $K(k_i) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1 - k_i^2 \sin^2 \theta}}$ (9)

and $k_i' = \sqrt{1 - k_i^2}$

so, we can calculate the effective permittivity that is

$$\epsilon_{eff} = 1 + \frac{\epsilon_r - 1}{2} \frac{k(k_2) k(k_1')}{k(k_2') k(k_1)} + \frac{\epsilon_r - \sqrt{\epsilon_r}}{2} \frac{k(k_s) k(k')}{k(k_s') k(k_1)} \quad (10)$$

Where, capacitance of C_{air} is defined as $2C_1 =$

$$4\epsilon_0 k(k_1) / k(k_1')$$

While, calculating the mathematical expression if there is no air pocket slot present in the CPW, then

$C_{slot} \rightarrow 0$ and $d \rightarrow 0$.

If we consider $a/b < 0$, then the effective permittivity is same as the CPW with h which is substrate height so, again the calculation will be

$$\epsilon_{eff} = 1 + \frac{\epsilon_r - 1}{2} \frac{k(k_2) k(k_1')}{k(k_2') k(k_1)} \quad (11)$$

So, we can calculate the effective permittivity and characteristic impedance of CPW chby putting these above equations.

IV. RESULTS AND DISCUSSION

A mathematical and simulation process is required to verify the relative permittivity,attenuation loss and loss tangent of coplanar waveguide with air pocket. In order to test the accuracy of the mathematical calculation proposed earlier, mathematical calculations were compared to matlab simulation of structures with varying slot depth d . To extract the capacitance we use matlab simulation in CPW and divide it by the capacitance of the CPW with the same aspect ratio suspended in air. The CPW had a geometry of $W=1\text{mm}$, $S=0.5\text{mm}$, and $h=0.813\text{mm}$,with the slot depth d as the variable being swept. In order test the validity of the approximation for materials with varying dielectrics constants, a variety of dielectrics were considered in this comparison.

The dielectrics used in the comparison,which is shown in the above fig.,consist FR-4 substrate which relative permittivity(ϵ_r) is 4.4 respectively. As we tasted the material ,the effective permittivity decreased as the slot depth increased. This was expected since the presence of air pockets reduces the effective dielectric area. This effect was particularly noticeable in material with higher permittivity like alumina and gallium arsenide.

To verify the mathe matical model for awide range of CPW aspect ratios, where $a/b = W/(W+2s)$,the above figure shows

the relative permittivities . The error is less than 5% for $0.3 \leq a/b \leq 0.7$ and upto 10% for more extreme a/b values in the range of $0.2 \leq a/b \leq 0.8$.

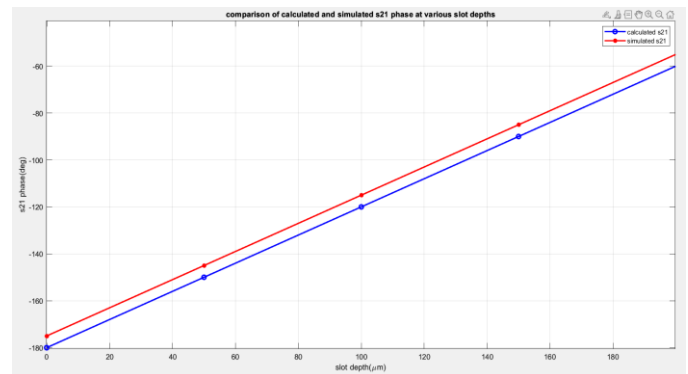


Fig.4 (comparison of effective permittivity mathematical calculation and matlab simulation)

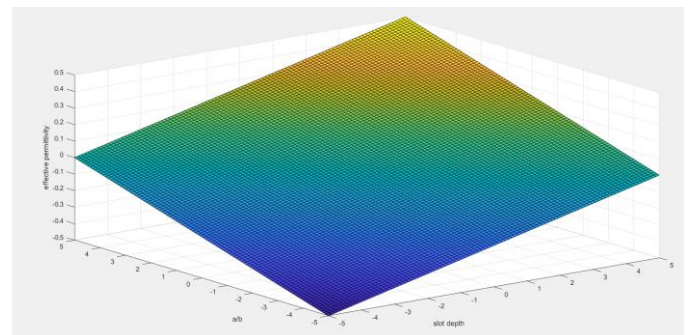


Fig.5 (simulation of CPW effective permittivity for various slot depth and a/b ratios on FR-4)

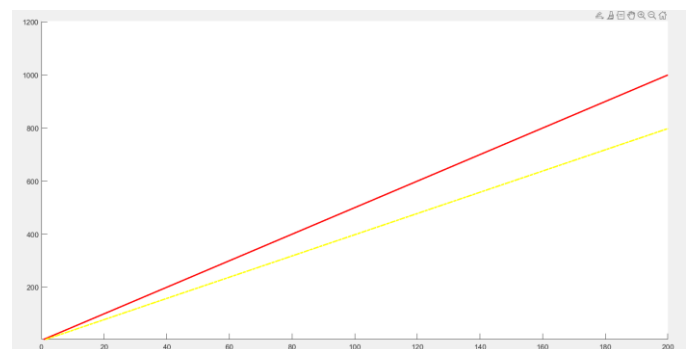


Fig.6 (comparison of calculated and simulated dielectric loss of CPW at various depth d)

The comparison of the calculated parameters is done against matlab simulation on FR-4 material with $\epsilon_r = 4.4$ and $\tan \delta = 0.02$. Theoretical and simulated structures were used to generate a frequency sweep of the attenuation constant α , with parameters $W = 1\text{mm}$, $S = 0.5\text{mm}$, $L = 20\text{mm}$, and $h = 0.813\text{mm}$. the attenuation constant was swept from $d = 0\mu\text{m}$ to $d = 200\mu\text{m}$ in steps of $50\mu\text{m}$ up to 18 GHz. The above

fig. shows a comparison between the calculated and simulated attenuation loss, with both magnitudes being comparable, especially at high frequencies

CONCLUSION

The use of air pocket slots in CPW structures leads to a decrease in effective permittivity as the slot depth is increased. This results in changes to the characteristic impedance and propagation constant for the CPW structure, which can have implications for the design of the thin-film circuits and microwave devices. The effectiveness of the partial capacitance approximation and calculations were confirmed through comparison with matlab simulations. The data was gathered to verify the impact of air pocket slots on propagation characteristics.

This included the effect on both effective permittivity and dielectric loss. The results of this study demonstrate that the CPW-AP structure with air pocket slots can be used to successfully extract the loss tangent of FR-4 material. To improve the methodology presented in this article for AM processes, it is recommended to incorporate machine learning (ML) and artificial intelligence (AI) models.

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