Short Papers

Efficient FDTD Analysis of Conductor-Backed CPW's with Reduced Leakage Loss

Masashi Hotta, Yongxi Qian, and Tatsuo Itoh

***Abstract*—Leakage loss of the conductor-backed coplanar waveguide (CBCPW) is analyzed by using a novel hybrid two-dimensional finite-difference time-domain/Marquardt curve-fitting technique. The validity and high accuracy of the method is confirmed by comparison with other experimental and theoretical results. A modified CBCPW structure with a substrate groove in the backside is proposed, which shows over eight times smaller leakage loss than a normal CBCPW.**

***Index Terms*—CBCPW, grooving substrate, leakage loss.**

I. Introduction

The coplanar waveguide (CPW) is a fundamental and important element for microwave integrated circuits (MIC's) and monolithic microwave integrated circuits (MMIC's) due to its ease for mounting active devices and its compatibility with the flip-chip technology. Although the original CPW structure [1] has a substrate without any metallization on the backside, in most practical applications, the substrate is backed with conducting material. The conductor-backed CPW (CBCPW) loses its modal power into leaky waves [2].

In this paper, the leakage loss of a CBCPW is analyzed by using a novel algorithm that combines two-dimensional finite-difference time-domain (2D-FDTD) full-wave analysis [3], [4] with Marquardt's curve-fitting technique [5]. This hybrid scheme is very efficient and gives accurate results compared to conventional three-dimensional finite-difference time-domain (3D-FDTD) analysis or the Prony's method [6], especially for structures where a single dominant mode is involved. It is also extremely general and can be applied to the analysis of microwave and millimeter-wave circuits with arbitrary cross sections. A potentially low-leakage loss CBCPW structure with modification of the substrate shape has been analyzed using this novel numerical technique. By introducing a substrate groove in the backside, a substantial reduction in leakage loss compared to a normal CBCPW has been demonstrated in simulations.

II. CBCPW and Leakage Loss Analysis

The structure of the CBCPW investigated in this paper is illustrated in Fig. 1, together with the coordinate system. It is assumed that the CBCPW has an infinite extension toward the $\pm y$-direction. The substrate used in this paper is GaAs with $\varepsilon_r = 12.9$ and $h = 100$ μm. Other parameters are $w = 120$ μm and $g = 96$ μm [7]. A perfect conductor with negligible thickness has been assumed here since it is well known that the propagation loss in the CBCPW is dominated by leakage loss into the parallel-plate mode.

First, the time variations of the electromagnetic fields are calculated using a 2D-FDTD algorithm [3], [4]. The FDTD cell sizes are selected mainly to discretize the structure as accurately as possible and are chosen as $\Delta x = 20.0$ μm and $\Delta y = 24.0$ μm, respectively. In this simulation, 60 and 173 cells are used for x- and y-directions, respectively. For the y-direction, the FDTD grid is truncated by the perfect matched layer (PML) [8] with ten-cell thickness and a fourth-order spatial polynomial for its conductivity profile. On the top and bottom surfaces, Mur's absorbing boundary conditions (ABC's) [9] are applied. Fig. 2 shows the time variation of the normal component E_x at the observation point placed at the center of the middle strip, corresponding to a predefined propagation constant $\beta = 3000$. Since only one dominant mode is supported in this CBCPW structure within the frequency range of our interest, we can accurately determine the modal frequency f and the time-domain attenuation constant α_t by applying the Marquardt's curve-fitting scheme as follows:

$$E_x(t) = A \exp(-\alpha_t t) \sin(2\pi f t + B) \tag{1}$$

where the coefficients A and B correspond to the initial amplitude and phase of E_x, respectively. Although (1) is only applicable to the case of single mode, it can be readily extended to the guided-mode analysis for multimode structures by using simple superposition. The major difference with the well-known Prony's method is that real functions are used here instead of the superposition of complex exponentials in the latter [6]. This not only makes the fitting procedure much simpler and more efficient numerically, but also presents better compatibility with FDTD since the time-signal E_x usually takes a real value in actual simulations.

Table I shows numerical results of α_t and f fitted for various values of β from 500 to 7000. In applying (1) to calculate α_t and f, it is usually sufficient to use only a few periods of oscillation. For the case of $\beta = 3000$, shown in Fig. 2, approximately 2000 time steps are enough. The lowest modal frequency corresponding to $\beta = 500$ requires approximately 6000 steps for the present structure.

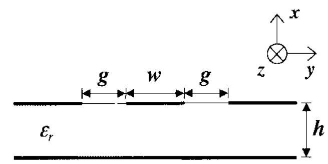

Fig. 1. CBCPW and coordinate system for the analysis.

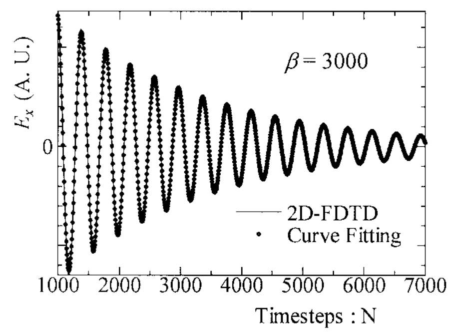

Fig. 2. Time oscillation of E_x at the observation point placed on the center of the middle strip of CBCPW obtained by the 2D-FDTD code and curve-fitting technique where $g = 96$ μm, $w = 120$ μm, $h = 100$ μm, $\varepsilon_r = 12.9$, and $\beta = 3000$.

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TABLE I
CURVE-FITTING FACTORS AND ATTENUATION CONSTANTS OF TIME SIGNAL ON THE CENTER OF THE MIDDLE STRIP OF THE CBCPW, WHERE PROPAGATION CONSTANTS ARE CHOSEN AS $\beta = 500$–7000

β	$2\pi f$ (rad./sec.)	f (GHz)	α_t (1/sec.)	α_s (dB/mm)	f (GHz) [FFT]
500	5.234E+10	8.330	2.361E+05	0.020	8.6
1000	1.045E+11	16.639	9.748E+05	0.081	16.8
1500	1.565E+11	24.908	2.205E+06	0.184	25.0
2000	2.082E+11	33.138	3.816E+06	0.318	33.3
2500	2.594E+11	41.283	5.683E+06	0.476	41.4
3000	3.099E+11	49.321	8.248E+06	0.694	49.4
3500	3.604E+11	57.357	1.068E+07	0.901	57.5
4000	4.101E+11	65.266	1.328E+07	1.125	65.4
4500	4.590E+11	73.054	1.635E+07	1.392	73.1
5000	5.078E+11	80.820	1.977E+07	1.690	80.9
5500	5.563E+11	88.546	2.293E+07	1.969	88.8
6000	6.041E+11	96.144	2.592E+07	2.236	96.4
6500	6.511E+11	103.632	2.905E+07	2.519	103.6
7000	6.978E+11	111.051	3.226E+07	2.811	110.8

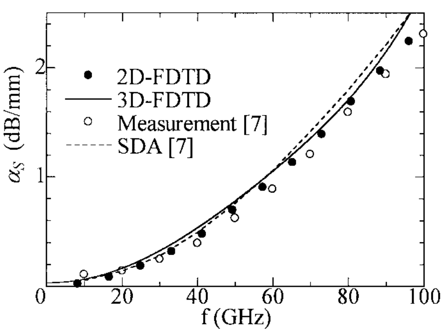

Fig. 3. Space-domain attenuation constants of conventional CBCPW as a function of frequency.

Meanwhile, since the dominant CBCPW is quasi-TEM in nature, we can calculate the space-domain attenuation constant α_s from the curve-fitted time-domain attenuation constant α_t using the following relation [6]:

$$\alpha_s = \alpha_t \beta / 2\pi f. \tag{2}$$

Fig. 3 plots the space-domain attenuation constant, as listed in Table I, as well as those calculated by the conventional 3D-FDTD method as a function of frequency. For comparison, the measured data and numerical results by spectral-domain analysis (SDA) [7] are also shown in the same figure. Very good agreement between the results obtained by the hybrid 2D-FDTD/Marquardt method and those by other experimental and theoretical approaches has been obtained, confirming the validity and accuracy of this new scheme.

Meanwhile, Fig. 4 shows the frequency-dispersion characteristics of the CBCPW. The two dispersion curves obtained by using a conventional fast Fourier transform (FFT) and the hybrid method agree very well, confirming once again the high accuracy of the proposed scheme.

III. NOVEL CBCPW WITH REDUCED-LEAKAGE LOSS

Using this new 2D-FDTD algorithm, we have simulated a potentially low-leakage-loss CBCPW with a groove on the backside, as shown in the inset of Fig. 5. The dimensions are assumed the same as that of the CBCPW in Fig. 2, except the grooving width L and depth h_1. Fig. 5 also plots the time variation of E_x at the observation point placed at the center of the middle strip, corresponding to the case of $\beta = 3000$, where the dimension of the groove is

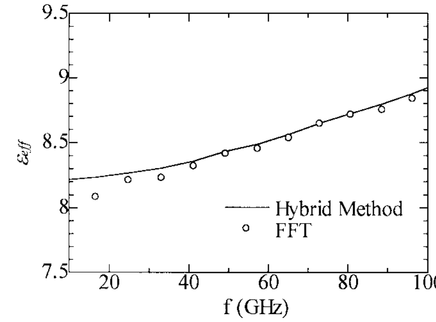

Fig. 4. Frequency dispersion characteristics (effective permittivities) of CBCPW obtained by the conventional FFT technique and hybrid method.

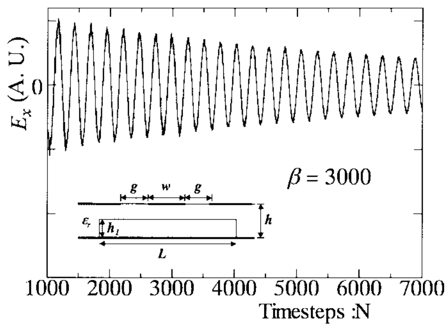

Fig. 5. Time oscillation of E_x at the observation point on the center of the middle strip of CBCPW with a groove where $h_1 = 60\ \mu$m and $L = 984\ \mu$m. The other parameters are the same as Fig. 2.

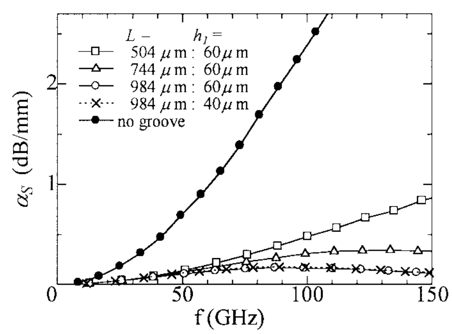

Fig. 6. Space-domain attenuation constants of CBCPW with grooving substrate.

$L = 984\ \mu$m and $h_1 = 60\ \mu$m. The attenuation constant in the space domain and the modal frequency obtained by the Marquardt curve fitting are 0.16 dB/mm and 75.2 GHz, respectively. For comparison, the frequency estimated by using the FFT is 75.3 GHz. At this frequency, the proposed CBCPW with a grooved substrate can reduce the leakage loss by over eight times compared to a conventional CBCPW with the same cross-sectional dimensions. Fig. 6 shows the frequency dependence of attenuation constants of CBCPW's with various groove lengths, as well as that of a conventional CBCPW. The effect of grooving depth ($h_1 = 60$ and $40\ \mu$m) on attenuation is also shown for the case of $L = 984\ \mu$m. As expected, the attenuation constant drops radically with the introduction of the groove, and decreases slightly when the groove length (L) is increased. Meanwhile, the grooving depth (h_1) is found to have less significant influence on the line loss as long as it is chosen to be around half of the substrate thickness. These results indicate that by modifying the substrate geometry using techniques such as backside etching or micromachining, we can design low-loss CBCPW structures to improve the performance of millimeter-wave MIC's and MMIC's. Alternative groove geometries, as well as their optimal dimensions for minimum leakage loss in CBCPW structures, will be investigated in the future.

IV. Conclusions

Power leakage characteristics of CBCPW's are studied with a novel hybrid 2D-FDTD/Marquardt curve-fitting technique. Attenuation constants obtained by this scheme agree well with independent theoretical and experimental results. This method is much faster than direct 3D-FDTD and more compatible with FDTD than the Prony's method, and can be readily applied to a wide range of microwave structures with arbitrary cross sections. Finally, a modified CBCPW structure with reduced leakage loss is proposed and analyzed. Numerical simulations indicate that the power decay in the CBCPW can be reduced significantly by introducing a substrate groove on its backside.

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