FDTD Analysis of Submillimeter-Wave CPW with Finite-Width Ground Metallization

Ngoc-Hoa Huynh and Wolfgang Heinrich

Abstract— **The dispersion and attenuation characteristics of conductor-backed coplanar transmission lines with finite-width ground metallizations are studied in the frequency range up to 1 THz. The finite-difference time-domain (FDTD) method is used for analysis. Open boundaries are described by means of Berenger's perfectly matched layer. The results are compared to electrooptic measurements. They show that introducing ground metallizations of finite width causes distinct changes in attenuation and dispersion characteristics.**

Index Terms— **CPW, FDTD method, submillimeter transmission line.**

I. Introduction

IN recent years, planar circuits for the submillimeter-wave frequency range have become a subject of increasing interest. Among the transmission lines used, the coplanar waveguide (CPW) plays a major role. In the past, analytic approximations were proposed to describe dispersion and attenuation characteristics [1], [2]. The formulas were verified by experimental data in the frequency range up to 1 THz [1]. In [3], CPW dispersion is calculated in time domain, but the frequency range is restricted to 300 GHz and attenuation is not given. The problem of leakage is treated in [4] and [5] where also the effects of conductor backing and finite lateral width are discussed on a qualitative basis. For the technically interesting CPW geometry, however, the conductor-backed structure with finite-width ground metallization, there is still a lack on simulation work, particularly regarding quantitative data.

The objective of the present paper is to clarify in which way finite lateral width influences the propagation behavior and to provide quantitative data for typical line geometries on semiconductor substrate. A further contribution refers to the method of analysis, the finite-difference time-domain method (FDTD). Berenger's perfectly matched layer (PML) is applied and found to be effective in modeling the open boundaries.

II. Structure and Method of Analysis

Fig. 1 illustrates the structure under investigation. High-resistivity silicon is used as substrate, but it can be replaced by GaAs without changing the characteristics basically. As in usual applications, the substrate backside is conducting and substrate thickness h is large compared with coplanar waveguide (CPW) ground-to-ground spacing $2s + w$. For our investigations, center strip width w and slot width s are kept constant ($w = 16$ μm, $s = 12$ μm) while ground-metallization width m is varied. Substrate thickness h_s is 380 μm. The top and the lateral boundaries are assumed to be open in order to include radiation effects.

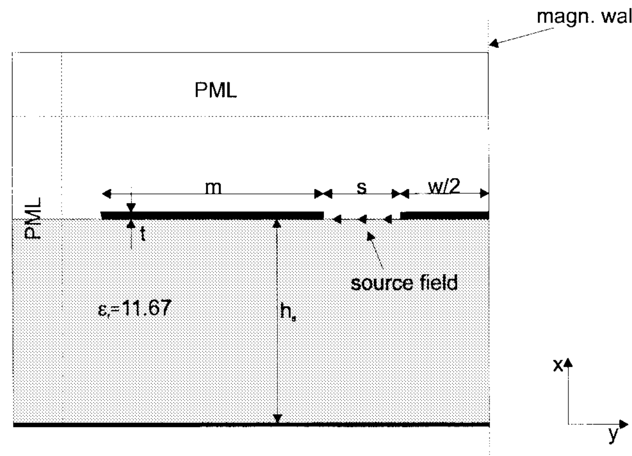

Fig. 1. FDTD model of the CPW structure under investigation, metal plane ideally conducting.

The waveguide in Fig. 1 supports two fundamental wave modes: the coplanar mode and the parallel-plate mode, which describes the floating potential between the ground conductor on the substrate surface and the backside metallization. In the lateral regions with metal-free substrate surface, one has the well-known dielectric-slab geometry supporting surface waves. The surface wave with the smallest cutoff frequency f_c is the TM_0 mode ($f_c = 0$), the highest order propagating modes in the frequency range up to 1 THz are TM_5 and TE_7.

We use the FDTD method to analyze the structures. The incident wave is excited by imposing the E_y component between center strip and ground metallization (Fig. 1). This ensures optimum decoupling to the parallel-plate mode so that the assumption of single-mode propagation is justified. The difference to the conventional way of a pulsed electric field hard source [7] is that within the source region the electromagnetic field is superposed and not replaced by the source field. This technique offers the advantage that the source is transparent to reflected waves. Sampling of the field is performed in the CPW slot also. Absorbing boundary condition PML layers [6] are placed laterally, on top, and in propagation direction. Due to symmetry, only half of the structure needs to be analyzed with a magnetic wall in the

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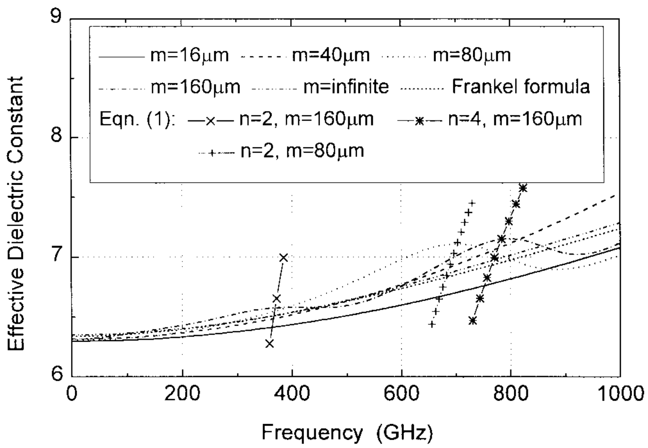

Fig. 2. Effective permittivity $\varepsilon_{\mathrm{reff}}$ of the CPW in Fig. 1 against frequency with ground-metallization width m as parameter (the bars denote the frequencies according to (1), also included are Frankel formula [1] and FDTD data for infinite ground plane, the dimensions are $w = 16\ \mu$m, $s = 12\ \mu$m, and $t = 0$).

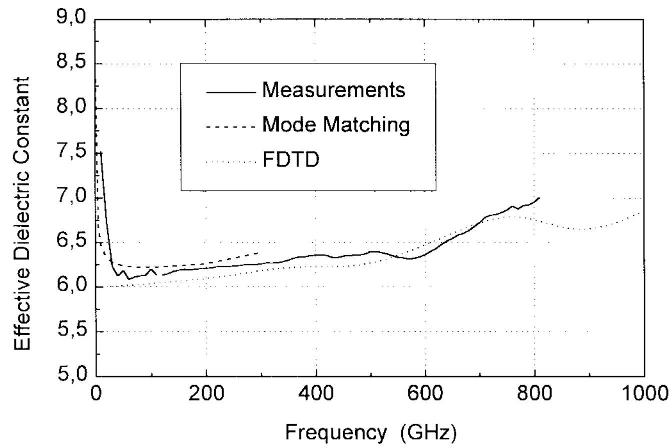

Fig. 4. Effective permittivity as a function of frequency for the structure of Fig. 2 with $m = 160\ \mu$m and $t = 0.8\ \mu$m: comparison of FDTD and mode-matching results (conductivity of metallizations $\kappa = 35$ S/μm) with electrooptic measurements.

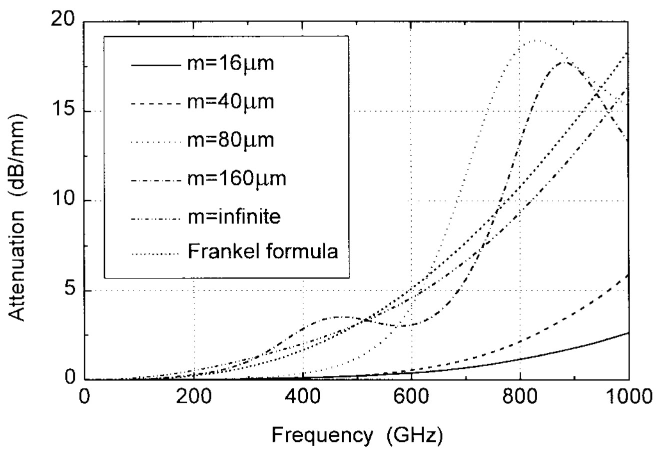

Fig. 3. Attenuation α as a function of frequency with ground-metallization width m as a parameter (dimensions as in Fig. 2); additionally included are the results for infinite ground plane by FDTD and Frankel [1].

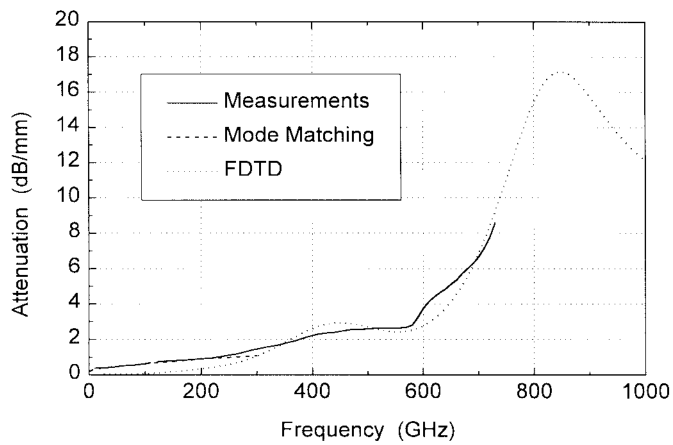

Fig. 5. Attenuation as a function of frequency for $m = 160\ \mu$m (other data as in Fig. 4).

center. A graded mesh is applied. Dispersion and attenuation of the coplanar mode are calculated from the Fourier-transformed electric fields at two locations along the CPW [3]. Substrate and conductor loss is neglected in the FDTD analysis. Thus, the resulting attenuation is only due to radiation. The mesh dimension for the structure with $m = 160\ \mu$m is $117 \times 103 \times 190$ cells. The simulation takes about 14 h on parallel DECmpp 12 000 machine (SIMD with 64×64 processor field, 1-GFLOPS peak performance).

III. Results

In Figs. 2 and 3, the behavior of $\varepsilon_{\mathrm{reff}} = (\beta/\beta_0)^2$ and α versus frequency is plotted with ground-plane width m as a parameter. The width m varies between 16 and 160 μm. All structures have zero metallization thickness ($t = 0$). With respect to $\varepsilon_{\mathrm{reff}}$, increasing the lateral width m from 16 to 160 μm raises dispersion slightly. More important is, however, that for $m = 80$ and $m = 160\ \mu$m the curves exhibit small local maxima. One finds that the maxima occur at frequencies where

$$\omega^2\mu\varepsilon - \left[\frac{n\pi}{\delta_1}\right]^2 = \beta_{\mathrm{cpw}}^2 \tag{1}$$

holds with $n = 2$ for $m = 80\ \mu$m and $n = 2, 4$ for $m = 160\ \mu$m, respectively (Fig. 2). $\delta_1 = 2m + 2s + w$ denotes the total CPW width including the ground planes. Equation (1) corresponds to the frequencies ω where multiples of the lateral wavelength of the waves in the substrate (propagation constant $\omega\sqrt{\mu\varepsilon}$) coincide with the total CPW width. Varying the substrate thickness h_s from 323 to 440 μm does not change the results. This differs from the Frankel formula [1] which predicts a distinct dependence on thickness h_s. In comparing both results one has to note, however, that the consideration in [1] refers to a structure without conductor backing and for thicknesses h_s in the range of $w + 2s$ whereas in our case a backside metallization exists with $h_s \gg w + 2s$.

For the attenuation, the influence of ground-metallization width m is more pronounced than for $\varepsilon_{\mathrm{reff}}$ (see Fig. 3). Clearly, a dependence on width m is observed. The general trend is: the larger m the larger the attenuation. The special feature is that maxima occur within the given frequency range for $m = 80$ and 160 μm. These maxima correspond to frequencies of (1) for $\delta_1 = 2m$. A possible explanation is the fact that the CPW mode excites waves propagating laterally toward the outer edge of the ground plane. In the case of an infinitely wide ground conductor ($m = \infty$) they cause leakage of the CPW mode [4], [5]. For finite width m, however, they are reflected at the outer edge of the ground plane forming a transverse standing-wave pattern. This leads to cancellation and resonance effects at certain frequencies and may cause enhanced attenuation of the CPW mode. However, this effect still needs a more detailed investigation.

Finally, in Figs. 4 and 5 a comparison with electrooptic measurements is presented for the CPW with $m = 160$ μm. The measurements were performed at the RWTH Aachen [8]. The mode-matching method is applied to calculate substrate and conductor loss (for the closed structure). Since these losses are not taken into account by the FDTD method, one has to add FDTD and mode-matching attenuation data to obtain a realistic value including all loss mechanisms. Generally, one finds good agreement with measurements.

IV. Conclusions

Focusing on conductor-backed submillimeter-wave CPW structures on Si or GaAs the results can be summarized as follows.

- The influence of finite ground-plane width m on effective permittivity is relatively small.
- Attenuation, on the other hand, is strongly affected. The values are considerably smaller than for infinite m and, in general, increase for growing width m.
- The effective permittivity and attenuation curves exhibit maxima indicating cancellation effects between different substrate modes.
- Substrate thickness values h_s much larger than ground-to-ground spacing $w + 2s$ do not influence phase constant and attenuation.
- The available approximations (e.g., [1]) fail to describe the case of finite lateral width accurately enough. This is true in particular for the attenuation characteristics.

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