Slow-wave Phenomena and Pulse Distortions in Optically Excited Schottky-contacted Coplanar Waveguide

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ABSTRACT

The slow-wave phenomena and the pulse distortions in optically excited Schottky-contacted coplanar waveguides are analyzed in this paper. The localized excitation model presented is formulated by the combination of the original and frequency-dependent versions of the FDTD method. Some attractive physical properties of Schottky-contacted CPW under optical illumination are examined.

INTRODUCTION

There has been increasing interest in the use of coplanar waveguides (CPW) in microwave and millimeter wave integrated circuits. Both theory and experiment verify the existence of slow-wave phenomena in CPW if a lossy layer is introduced and the central conductor is reverse- biased [1-3]. This forms the physical foundation for variable phase shifters. When the lossy layer is generated by the combination of electrical and optical approaches, a class of optically controlled Schottky contacted phase shifters result [4]. Recently, a new optically controlled CPW phase shifter on optically transparent quartz instead of on semi-insulating GaAs substrate has been fabricated using the epitaxial lift off (ELO) technique[5]. The ELO device allows the back-side illumination, avoiding any metal shadowing effects, thus exhibiting a significant improvement in performance.

In order to understand the physical insight into the CPW phase shifters and select the type of the structures in practical applications, this paper introduces an intensive analysis of the slow-wave phenomena and the pulse distortions in optically excited Schottky-contacted CPW. A localized excitation model is presented, which is formulated by the combination of original and frequency-dependent versions of the FDTD method. Some interesting results are presented and discussed.

FORMULATION

Fig.1 shows a localized excitation model under consideration, where it is assumed that the optical interaction with active layer in CPW takes place in region I only. This is obviously the case where the illumination is from the backside. Of course, the slight modification of Fig.1 to account for any metal shadowing effects due to the front-side illumination is straightforward.

a. Slow wave phenomena

When the slow wave propagation is to be analyzed, the typical 2D problem will be involved. To this end we adopt 2D compact FDTD scheme. But some modifications to the original version must be made to account for the frequency dependent permittivity of optically generated electron-hole plasma in region I. In addition, for those cells that are located at the interface between region I and adjacent regions, special FDTD schemes need to be established from the integral form of Maxwell's equation.

For our problem, because the dimensions of the structure are very small, a very fine spatial

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discretization is usually required. The stability condition of the FDTD scheme requires that the corresponding timestep Δt should also be very fine. This implies that many iteration steps are required until the temporary response reaches its stable state. To overcome this problem, the sheet admittance is used to model the thin insulated layer h_1, reducing the number of the spatial grids. Furthermore, we adopt the time series analysis similar to [6]. Numerical experiments show that if the initial excitation is accurate enough, the time series analysis will provide acceptably accurate results for the frequency domain parameters. The idea of the time series analysis stems from a priori knowledge that the time domain response of the launched excitation is a damped sinusoidal wave if the absorption due to optically generated plasma is incorporated. Choose the voltage v_i, defined as the linear integral of the electric field along the slot, as a parameter to be tested. The damped wave is fitted by an explicit function as

$$v_i(n\Delta t) = A e^{-c_1 n\Delta t} \cos(c_2 n\Delta t + \phi) \quad (1)$$

where the unknown coefficients A, c1, c2, ϕ are determined using Powell optimization technique. From eqn.(1) we obtain the slow wave factor λ_0 / λ_g and attenuation constant α:

$$\frac{\lambda_0}{\lambda_g} = \frac{v_0 \beta}{c_2} \quad (2a)$$

$$\alpha = c_1 \left(\frac{dc_2}{d\beta}\right)^{-1} \quad (2b)$$

It should be noted that the formula for α in eqn.(2b) differs from that given in [6]. From the electromagnetic point of view, our formula represents a more rigorous definition.

b. Pulse distortions

The change in the waveform the pulse signal undergoes is evaluated by carrying out the 3D FDTD simulation. Similar to the 2D case, the original version of the FDTD must be modified in region I to account for the dispersive property of the permittivity. Our FDTD scheme is the extension of that given in [7]. The recursive implementation scheme for E-field components similar to that in [7] is also derived for our problem. At the interface between region I and adjacent regions, the FDTD scheme for the tangential electric fields is established from the integral form of Maxwell's equation:

$$\int_c \overline{H} \cdot \overline{dl} = \iint_s \epsilon(\bar{r}) \, \overline{E} \cdot \overline{ds} \quad (3)$$

Because the insulated layer d_1 is usually very thin, its direct inclusion in FDTD will result in very fine spatial discretization. A sheet admittance is used to model the thin insulated layer as

$$Y_s = j\omega\epsilon_0(\epsilon_{r1} - 1)d_1 \quad (4)$$

The source and end planes are terminated by a 2-order ABC.

c. Initial excitation

The successive excitation is used. First, we calculate the static field distribution using the finite difference method in conjunction with the asymptotic boundary condition [8]. The static solution above is used as the initial excitation of 2D FDTD simulation. And then, for a certain propagation β, record the simulation results for E fields at a certain time step t_n. The dynamic fields are further used as the spatial distribution of the 3D FDTD excitation. The excitation mechanisms outlined above have proven to be efficient and can prevent the oscillating phenomena from apperaring at the initial stage, as seen in the rough estimations.

NUMERICAL EXPERIMENTS

A typical optically controlled Schottky contacted CPW on quartz substrate has been simulated. The physical parameters are chosen as follows: w = 45 μm, s = 50 μm, w_p = 145 μm, t = 0 μm, d_1 = 0.5 μm, d_2 = 10 μm, ϵ_{r1} = 8.5, ϵ_{r2} = 13.0, ϵ_{r3} = 8.0. The complex permittivity ϵ_{rp} in region I is found from the well known Drude-Lorentz formula[9]. The optical parameters involved in ϵ_{rp} for GaAs material are quoted from [9].

Fig.2 shows the slow-wave characteristics of CPW. It is seen that the slow-wave factor and the attenuation constant are highly sensitive to the density of the electron-hole plasma in region I. Figs.3 (a) and (b) show the typical temporarey time responses of a launched Gaussian pulse under the two different illumination levels. Comparison of Figs.3(a) and (b) reveals that the optical illumination not only disperses the pulse waveform, but also results in an appreciable tail in the pulse signal waveform.

CONCLUSIONS

The slow-wave phenomena and the pulse distortions in optically excited Schottky-contacted coplanar waveguides have been analyzed using the combination of original and frequency-dependent versions of the FDTD method. The excitation model considers the optical interaction with microwaves in the CPW structures to be localized under the center conducter. The modification to the model can account for the metal shadowing effects. The results presented show that: ✦ The optically excited Schottky-contacted CPW indeed supports a slow-wave mode when the illumination is intensive enough; ✦ The slow-wave factor and attenuation constant are frequency dependent as well as controllable by the illumination intensity; and ✦ When a pulse signal propagates along CPW, the optically generated electron-hole plasma, due to the dispersive nature of its complex permittivity, cause a significant spread of the waveform and produce a long appreciable tail in the pulse signal.

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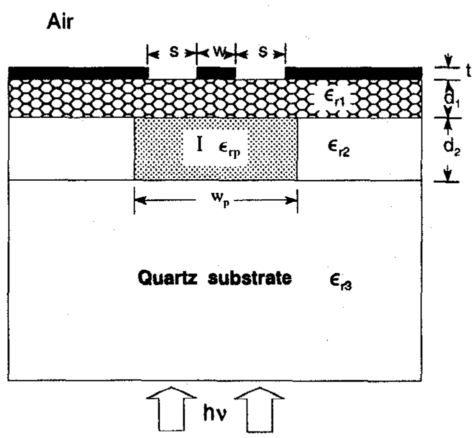
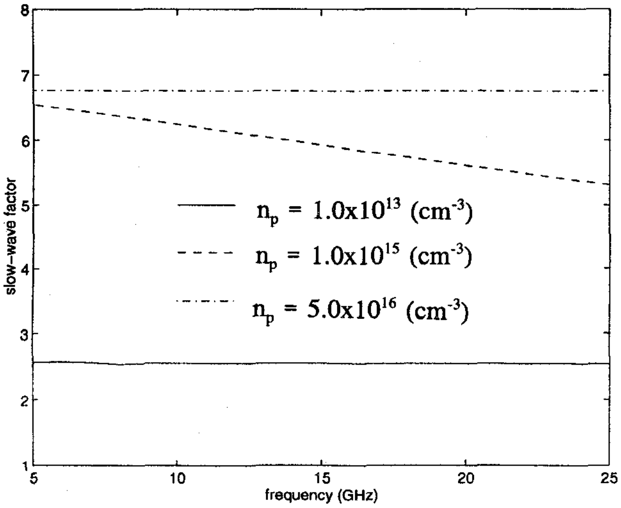
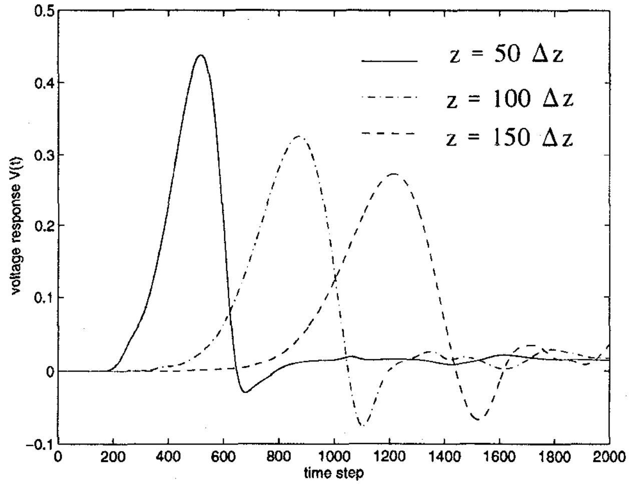


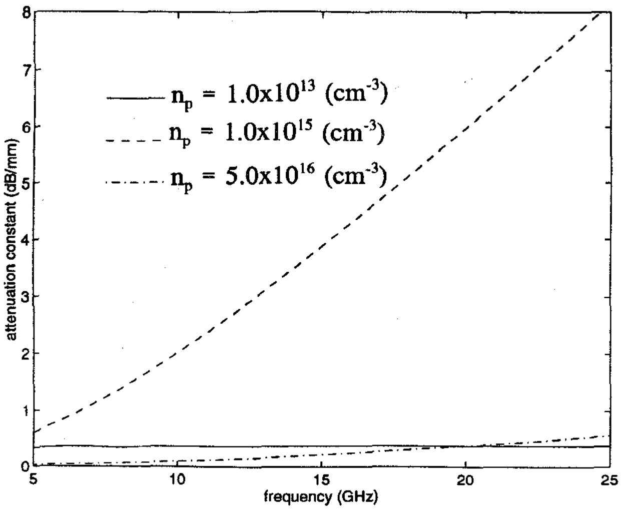
Fig.1 Localized excitation model for Schottky contacted CPW under optical illumination



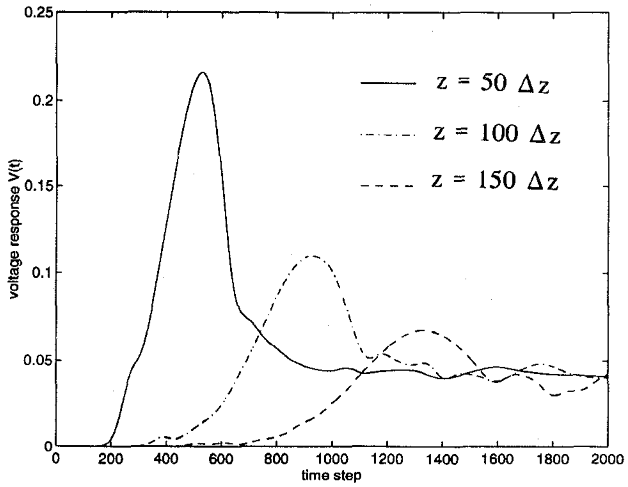
(a) slow-wave factor



(a) n_p = 1.0x10^{13} (cm^{-3})



(b) attenuation constant



(b) n_p = 1.0x10^{15} (cm^{-3})

Fig.2 Slow-wave characteristics of optically excited Shottky contacted CPW

Fig.3 Pulse distortions in optically excited Shottky contacted CPW