Numerical Investigation of External Electromagnetic Field Coupling to Coplanar Waveguide

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A B S T R A C T

In this paper, for the first time, effects of external electromagnetic fields on a coplanar waveguide (CPW) are numerically studied by means of the method of finite elements. Two CPW lines with different geometry and dielectric substrate permittivity are considered. Both lines have characteristic impedance of 50 Ω. Induced electric and magnetic fields on the two CPW lines are analyzed by illuminating the structure with a plane wave. The uniform plane wave with fixed frequency at 3 GHz is considered as the incident field. The influences of the incidence angle and dielectric substrate permittivity are investigated. For this purpose, two incidence planes are considered and, for each case, two polarizations, parallel and perpendicular, for incidence electric field relative to incidence planes are studied. According to the results, for the two CPW lines terminated with their characteristic impedance at both ends and the incident plane wave with electric-field intensity of 1 V/m at f = 3 GHz with incidence angles of 22.5˚ and 45˚, maximum peaks of the induced field occur and also, depending on the incidence plane, incidence angle and E-field polarization, even or odd quasi-TEM mode of the CPW line can be propagated.

I. INTRODUCTION

In recent years, with increasing demand for higher speeds and high amount of transmitted information, ensuring signal integrity has become a major problem [1]-[3]. Existence of electromagnetic fields in the environment can affect the performance of transmission lines. External electromagnetic fields can induce the voltage and current on the transmission lines and cause interference [4]-[6]. This problem can be more important when high immunity is required and so needs more attention. The external electromagnetic field coupling to transmission lines has been evaluated in many works. An overview of field to transmission line coupling models is presented in [7]. For nonuniform lossy transmission lines, equivalent-circuit modeling considering the coupling of an incident field was proposed in [8]. A model for the fields

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coupling with two connected transmission lines with different reference planes was presented in [9]. The external electromagnetic field coupling to transmission lines loaded in the metallic enclosure with apertures was evaluated based on the extended Baum-Liu-Tesche (BLT) equation in [10] and the analytical modeling was proposed. In [11], a time-domain response of twisted-wire pairs illuminated by an external incident electromagnetic field was calculated by finite-difference time-domain (FDTD) method. In [12], a numerical analysis method was proposed for the electromagnetic coupling problem on the cables of aircraft fuel measurement system.

However, due to low-profile, low-cost and ability for integration with planar circuits, the use of planar integrated circuits in the design and production of electronic components has been increased. There are several planar transmission lines such as microstrip line, strip line, slot line, coplanar waveguide (CPW), etc [13]; these are an ordinary select where a connection is needed for planar circuits.

Effects of external electromagnetic field on a microstrip line

were studied in [14] and the induced voltage and current were investigated using a distributed-source transmission-line model. In [15], effects of electromagnetic field coupling to microstrip line connected with nonlinear components were analyzed, in which for the nonlinear component, the voltage and current responses as well as the its transmitted power to the next one were obtained. A method for studying the effect of electromagnetic field interference of on-board antenna to transmission lines was presented in [16]. Differential to common mode coupling due to any discontinuities in the coupled microstrip lines was investigated in [17]. Coupling models for the two orthogonal microstrip lines and orthogonal strip lines in multilayer PCB were proposed in [18], [19] and a lumped equivalent circuit was introduced. In addition, an analytical method was proposed in [3] for describing crossing strip junctions with regard to signal integrity analysis.

The CPW is one of important planar transmission lines in microwave and millimeter wave circuits that is suitable for active and passive circuits. The CPW offers several advantages such as easy fabrication, low radiation loss and low cross talk effects between adjacent lines [20]. In this paper, for the first time, the effect of external electromagnetic field on a CPW is numerically investigated by finite elements method. For this purpose, two CPW structures with different geometry and dielectric substrate permittivity are considered. Both transmission line structures are illuminated by a uniform plane wave with different incidence angles. For each case, two incidence planes with two electric field polarizations, parallel and perpendicular relative to incidence planes are considered and the induced electric and magnetic fields along the lines are examined.

II. COPLANAR WAVEGUIDE STRUCTURE

The geometry of a CPW is illustrated in Fig. 1. A CPW center metal strip with the width of S and the distance of separation between the two semi-infinite ground planes of b is placed on a dielectric substrate with the thickness of h and relative permittivity of ε_r. Even or odd quasi-TEM mode can be propagated by this structure [13], [20]. Electric and magnetic field lines of these two modes of the CPW are shown in Fig.2. In the even mode, electric fields in the two slots are in the opposite direction and electric fields in odd mode in the two slots are in the same direction. The characteristic impedance (Z_0) and effective relative permittivity (ε_{eff}) of the quasi-TEM mode in CPW structure can be calculated by Equs (1)-(2) [20]:

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff}}} \frac{K(k'_0)}{K(k_0)} \tag{1}$$

$$\varepsilon_{eff} = 1 + \frac{\varepsilon_r - 1}{2} \frac{K(k_1)}{K(k'_1)} \frac{K(k'_0)}{K(k_0)} \tag{2}$$

where $K()$ is the complete elliptic integrals and k_0 , k'_0 k_1 , k'_1

are:
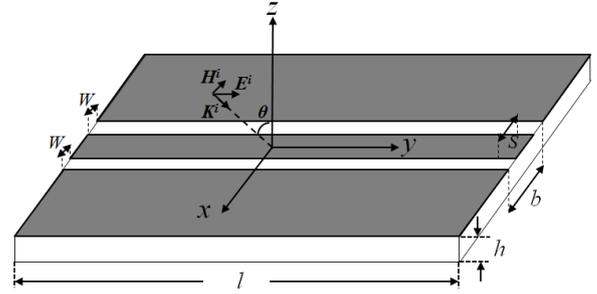
Fig. 1. CPW structure illuminated by an uniform plane wave.

(a)

(b)

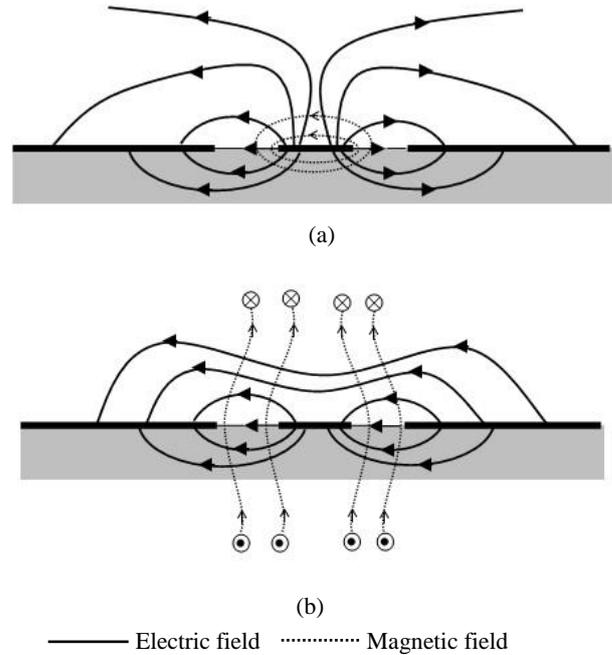——— Electric field   ············· Magnetic field

Fig. 2. Electric and magnetic field lines in the cross section of the CPW: (a) even mode (b) odd mode.

$$k_0 = \frac{S}{S + 2W} \tag{3}$$

$$k'_0 = \sqrt{1 - k_0^2} \tag{4}$$

$$k_1 = \frac{\sinh(\pi S/4h)}{\sinh\{[\pi(S + 2W)]/4h\}} \tag{5}$$

$$k'_1 = \sqrt{1 - k_1^2} \tag{6}$$

As shown in Fig. 1, this transmission line structure is illuminated by a time-harmonic uniform plane wave with the frequency of f. The incident field is propagating in the $\hat{z}_i$ direction that forms angle θ with the normal to the CPW plane:

$$E^i = E_0 e^{-jK_0\hat{z}_i.r} \tag{7}$$

$$H^i = \frac{1}{\eta} \hat{z}_i \times E_0 e^{-jK_0\hat{z}_i.r} \tag{8}$$

where K_0 is the propagation constant, η is the intrinsic impedance of the free space and r is the position vector. The
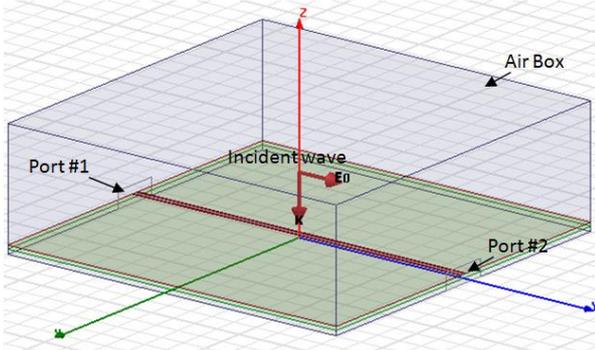

Fig. 3. Simulation of a CPW line excited by an electromagnetic field

external fields inducing the electromagnetic fields on the CPW line depend on the directions of electric and magnetic fields. Also, characteristics of the dielectric substrate of the CPW can influence the coupling phenomenon.

III. SIMULATED RESULTS AND DISCUSSION

To examine the effects of an external plane wave and geometrical characteristics of the CPW line, two CPW lines were considered and numerically investigated. Both lines were studied based on the finite element method (FEM) using high frequency structure simulation (HFSS) [21]. For the following computations, the substrate thickness of 1.57 mm and characteristic impedance of 50 Ω were considered for both lines. In the simulation, both lines included two ports at both ends that were equivalent to terminating by matched load. Fig.3 shows the simulation carried out using HFSS. The length of the two lines was 150 mm. The first CPW line had the center metal strip with the width of $S = 5$ mm, slots width of $W = 0.2$ mm and dielectric substrate relative permittivity of $\varepsilon_r = 2.55$. The second CPW line had center metal strip with the width of $S = 2$ mm, slots width of $W = 0.7$ mm and dielectric substrate relative permittivity of $\varepsilon_r = 10$. The uniform plane wave with the electric field intensity of 1 V/m and frequency of 3 GHz was considered as the incident field.

To examine the effect of external electromagnetic field to CPW line, two incidence planes consisted of x-z plane and y-z plane and, for each plane, two E-field polarizations (parallel and perpendicular polarizations relative to incidence plane) were considered. Simulations were performed for the incidence angles of 0, 22.5, 45, 67.5 and 80 degrees. Peaks of the induced electric and magnetic fields for the two CPW lines are shown in Figs. 4-5. It can be found for both CPW lines that the peaks of the induced electric and magnetic fields for the y-z incidence plane were larger than those for the x-z incidence plane for both parallel and perpendicular polarizations. Also, approximately for the incidence angles of 22.5˚ and 45˚,

maximum peaks of the induced field occurred. In addition, the simulated results showed the peaks of the induced electric and magnetic fields for the CPW line with $\varepsilon_r = 2.55$ were approximately greater than those of the CPW line with $\varepsilon_r = 10$.

Figs. 6-7 show the induced electric field distribution of the center metal strip and cross-section of CPW lines with $\varepsilon_r = 2.55$ and $\varepsilon_r = 10$ for the incidence planes of x-z and y-z planes, $\theta_i = 22.5˚$ and perpendicular polarizations. For the incidence planes of x-z and perpendicular polarizations that the incident electric field E^i directed as the y axis, it is observed that the induced electric fields in the two slots of the CPW line were in the opposite direction and the even mode was propagated in the CPW line. For the incidence planes of y-z and perpendicular polarizations that the incident electricfield E^i directed as the x axis, the induced electric fields in the two slots were in the same direction and the odd mode was propagated in the CPW line. Accordingly, the variation of the electric field distribution of along the CPW line was fasterin the CPW line with $\varepsilon_r = 10$ than the CPW line with $\varepsilon_r = 2.25$, which was due to higher permittivity of the substrate.
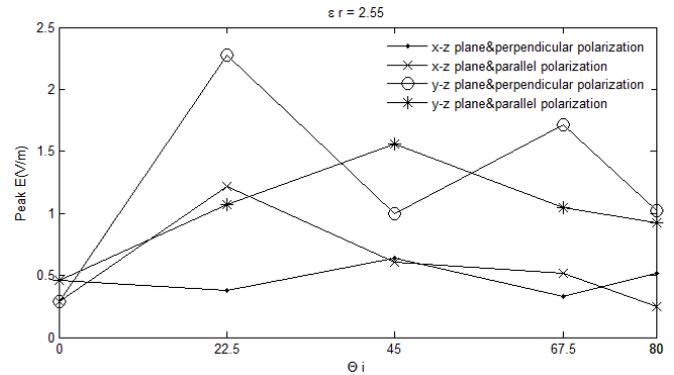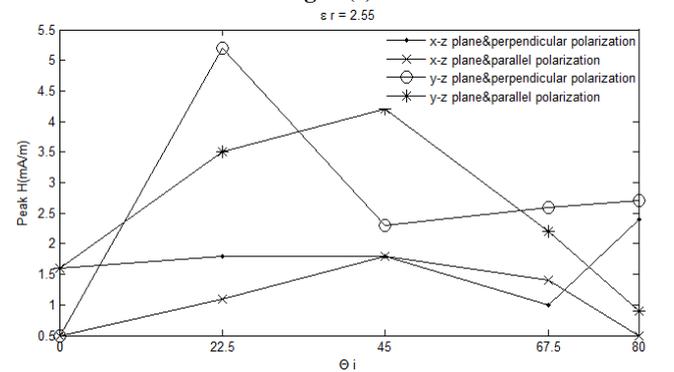

Fig. 4 (a)

Fig. 4 (b)

Fig. 4. (a) Peaks of the induced electric field **(b)** Peaks of the induced magnetic field for the CPW line with $\varepsilon_r = 2.55$
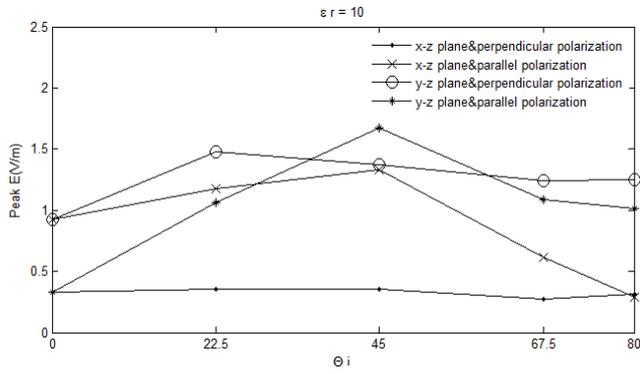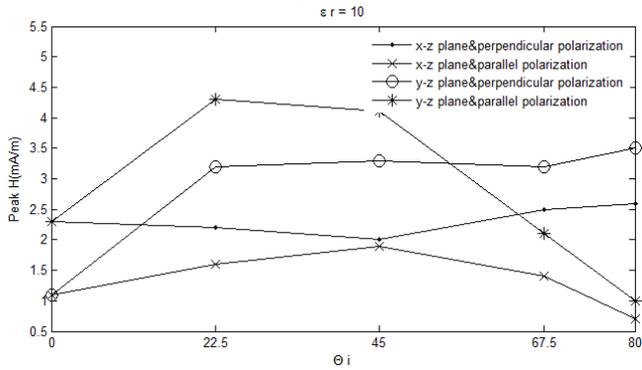
Fig. 5. (a)

Fig. 5. (b)

Fig. 5. (a) Peaks of the induced electric field **(b)** Peaks of the induced magnetic field for the CPW line with $\varepsilon_r = 10$.
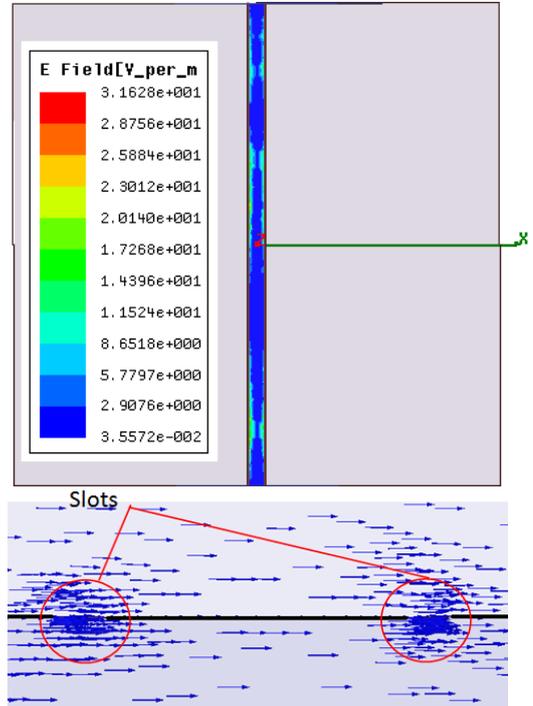

Fig. 6 (b)

Fig. 6. Induced electric field distribution of the center metal strip and cross section of CPW lines with $\varepsilon_r = 2.55$ for $\theta_i = 22.5°$, perpendicular polarizations and (a) incidence plane of x-z (b) incidence plane of y-z.

Fig. 6 (a)

Fig. 7. (a)

Fig. 7. (b)

Fig. 7. Induced electric field distribution of the center metal strip and cross section of CPW lines with $\varepsilon_r = 10$ for $\theta_i = 22.5°$, perpendicular polarizations and (a) incidence plane of x-z (b) incidence plane of y-z.
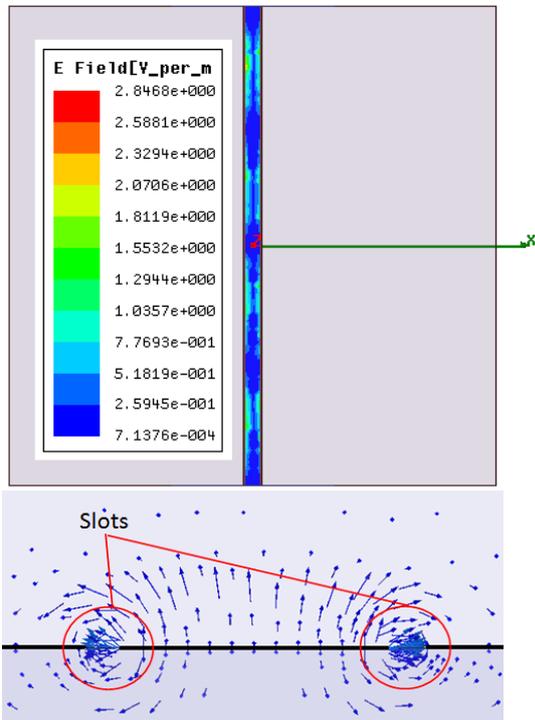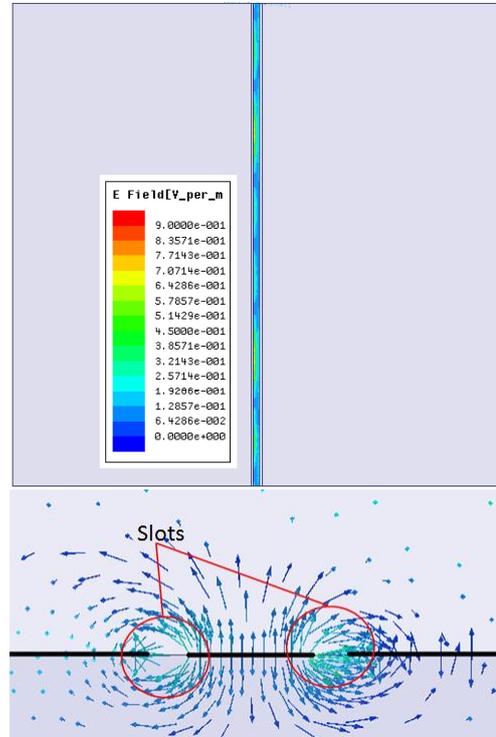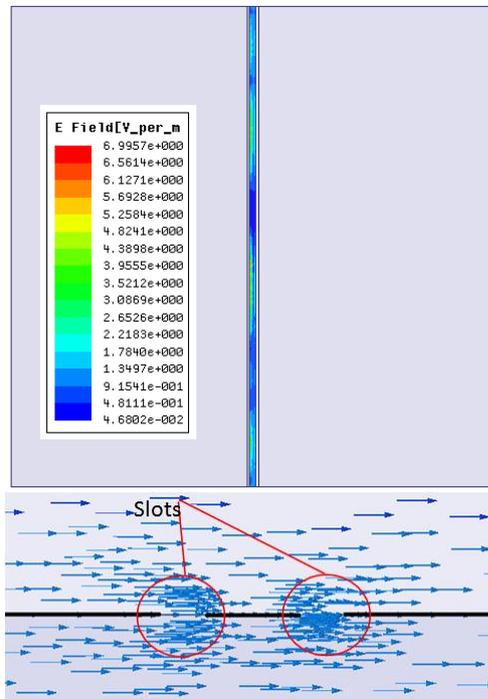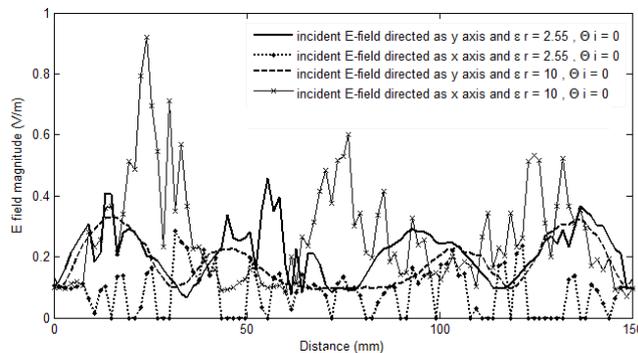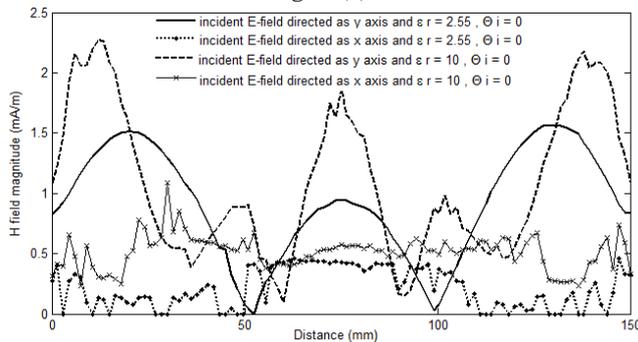

Fig. 8. (a)

Fig. 8. (b)

Fig. 8. (a) Magnitude of the induced electric field (b) Magnitude of the induced magnetic field along the CPW lines with $\varepsilon_r = 2.55$ and $\varepsilon_r = 10$ for incidence angle $\theta_i = 0°$

Magnitude of the induced electric and magnetic fields along the CPW lines with $\varepsilon_r = 2.55$ and $\varepsilon_r = 10$ for incidence angle $\theta_i = 0°$ (incident wave in the z direction) is shown in Fig. 8. For the CPW line with $\varepsilon_r = 10$, the magnitude of the induced electric field when the incident electric field E^i directed as the x axis was more than other states and the magnitude of the induced magnetic field when the incident electric field E^i directed as the y axis was more than other states. In the case of incidence angle $\theta_i = 0°$, the amplitudes of the induced electric and magnetic fields were approximately symmetric with respect to the center of the line. In this case as well, when the incident electric field E^i directed as the y axis, the even mode was propagated and, when the incident electric field E^i directed as the x axis, the odd mode was propagated.

IV. CONCLUSIONS

In this paper, the coupling between an external electromagnetic field and the CPW line was investigated. The electric and magnetic fields induced along the line by the external plane wave were analyzed. Effects of the incidence plane, incidence angle and dielectric substrate permittivity on the coupling were evaluated. Two CPW lines with the characteristic impedance of 50Ω and dielectric substrate relative permittivity of 2.55 and 10 were considered. Both lines terminated with their characteristic impedance at both ends. For each case, two incidence planes and, for each plane, two E-field polarizations, parallel and perpendicular relative to incidence plane and incidence angles of 0, 22.5, 45, 67.5 and 80 degrees, were examined. The simulated results showed for the incidence angles of 22.5° and 45°, maximum peaks of the induced field occurred. Also in these cases, depending on the incidence plane, incidence angle and E-field polarization, even or odd quasi-TEM mode of the CPW line could be propagated.

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