Effects from the Thin Metallic Substrate Sandwiched in Planar Multilayer Microstrip Lines

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Abstract—This paper studies the dispersion characteristics of open multilayer microstrip lines with a thin highly-conductive metallic substrate using the spectral domain approach. From the numerical results, it is found that, in both lossy (metal-insulator-silicon structure such as Si-SiO_2) and lossless configurations (thin metal between lossless dielectric microstrip line), at the low frequency range, this thin metallic substrate can excite slow waves. And accordingly the frequency dependent transmission-line characteristics of interconnects, such as propagation constant, attenuation and the characteristic impedance, can change remarkably with the existence of the thin metallic substrate.

1. Introduction

The lossy transmission line structures gain more attentions due to the fast development of the VLSI semiconductor circuits. In this case, multilevel interconnect networks are introduced into multilayer silicon structures to enable great efficiency of semiconductor integration. But this is also accompanied with many challenges to interconnect in circuit design. From the viewpoint of signal integrity, these complicated structures of interconnect network make the circuit much vulnerable to the substrate coupling of noise, power supply noise, ground bounce, crosstalk, ringing, antenna effects etc.

As one solution, very thin highly-conductive substrates are added into multilayer structures as ground to depress or shield away the harsh effects. Cregut et al., showed that, by certain metallic substrate configuration, the crosstalk can be reduced as well as the transient performance improved [1]. However, at some low RF and microwave frequencies, the skin depth may be much larger than the metal thickness of profile. The electromagnetic wave can penetrate the thin metallic substrate and reach further deeply into the layers underneath. In another words, the electromagnetic wave can "see through" and consequently interact with the multilayer configuration underneath. Considering this phenomenon, Song et al. found the frequency dependent characteristics or dispersion characteristics of interconnects, such as resistance, inductance, capacitance, and conductance (RLCG) per unit length, change remarkably with the existence of thin metallic substrate [2].

The previous work of planar multilayer microstrip line starts with the hypothesis of the perfect electric conductor (PEC) ground plane or impedance boundary condition (IBC), and considers the effects of the strip with finite conductivity or thickness. This paper focus on the effects of this thin but highly conductive substrate in the middle substrate. To adequately analyze this effect, the spectral domain approach (SDA) is used [3, 4]. The simplified model of an open microstrip line is proposed, and the corresponding 2-dimensional Green's functions of multilayer microstrip line are deduced. The method of moments is applied to solve the related eigenvalue problem numerically. Thus the dispersion performances of the propagation constant, attenuation and the impedance of open multilayer microstrip lines are simulated numerically. It also shows that the slow wave can be excited.

2. Modelling and Spectral Domain Approach

The open microstrip line with considered thin metallic substrate is shown in Figure 1. The substrates are assumed to be uniform and infinite in both the x and z directions. The signal strip as well as the lowest ground plane is taken as infinitesimally thin and PEC. After taking a spatial Fourier transformation in the x direction, the coupled integral equations on the surface of the strip line become the algebraic ones as following

$$\begin{bmatrix} \tilde{E}_x(\alpha, y_s) \\ \tilde{E}_z(\alpha, y_s) \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{xx}(\alpha, y_s) & \tilde{Z}_{xz}(\alpha, y_s) \\ \tilde{Z}_{zx}(\alpha, y_s) & \tilde{Z}_{zz}(\alpha, y_s) \end{bmatrix} \begin{bmatrix} \tilde{J}_x \\ \tilde{J}_z \end{bmatrix} \tag{1}$$

where $\tilde{Z}_{xx}$, $\tilde{Z}_{xz}$, $\tilde{Z}_{zx}$ and $\tilde{Z}_{zz}$ are the dyadic Green's functions for microstrip geometry. α denotes the spectral domain variable in x direction. y_s stands for the interface where the signal strip located on. The immittance approach [3] decouples the field into two independent configurations as transverse electric (TE^y) and transverse magnetic (TM^y) modes. Using the transmission line modelling (TLM), the Green's functions are derived as parallel combination of the admittance seen above and below the interface y_s. Then the Galerkin's method

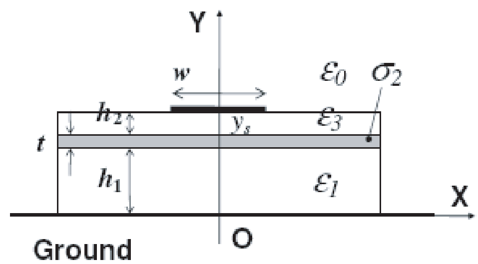


Figure 1: Configuration of 3-layer open microstrip line with very thin metallic substrate with thickness t (grey).

is used to solve the equation (1) for the propagation constant. The current density $\tilde{J}_x$ and $\tilde{J}_z$ are separately expanded into a series of basis functions as

$$\tilde{J}_x = \sum_{m=1}^{M} a_m \tilde{J}_{xm}, \quad \tilde{J}_z = \sum_{n=1}^{N} b_n \tilde{J}_{zn}, \tag{2}$$

where the a_m and b_n are the coefficients of current basis function. After substituting the current expansions (2) into (1) and doing the scalar product on both sides, based on the Parseval theorem, the integral equation is discretized into a homogeneous system with $M + N$ linear equations. Consequently the value of propagation constant is directly correspondent to the eigenvalue of the system which makes the determinant of the following equation equal to zero.

$$\begin{aligned} &\sum_{m=1}^{M} a_m K_{i,m}^{xx} + \sum_{n=1}^{N} b_n K_{i,n}^{xz} = 0 \quad (i = 1, \ldots, M) \\ &\sum_{m=1}^{M} a_m K_{j,m}^{zx} + \sum_{n=1}^{N} b_n K_{j,n}^{zz} = 0 \quad (j = 1, \ldots, N) \end{aligned} \tag{3}$$

The real part of the complex wave number is related directly with the propagation wavelength and phase velocity while the imaginary part is the attenuation per unit length along the z direction.

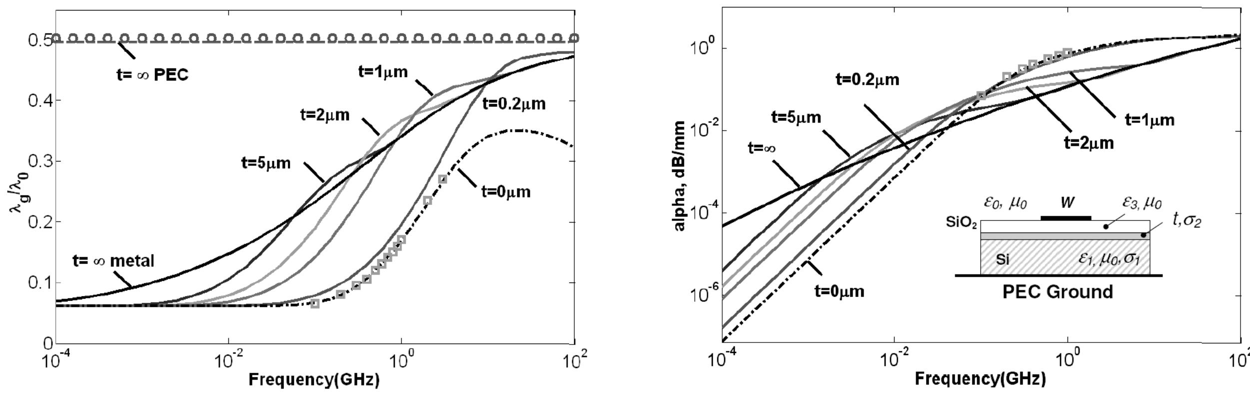
3. Dispersion Characteristics

In this section, the influences of this very thin metallic substrate on the performance of microstrip are simulated. One thin metallic substrate is inserted into a metal-insulator-semiconductor (MIS) structure and a lossless microstrip line, which results in two multilayer cases respectively: the metal-insulator-metal-semiconductor (MIMS) and metal-insulator-metal-insulator (MIMI) to be studied in the following.

3.1. Very Thin Metallic Substrate in Lossy System

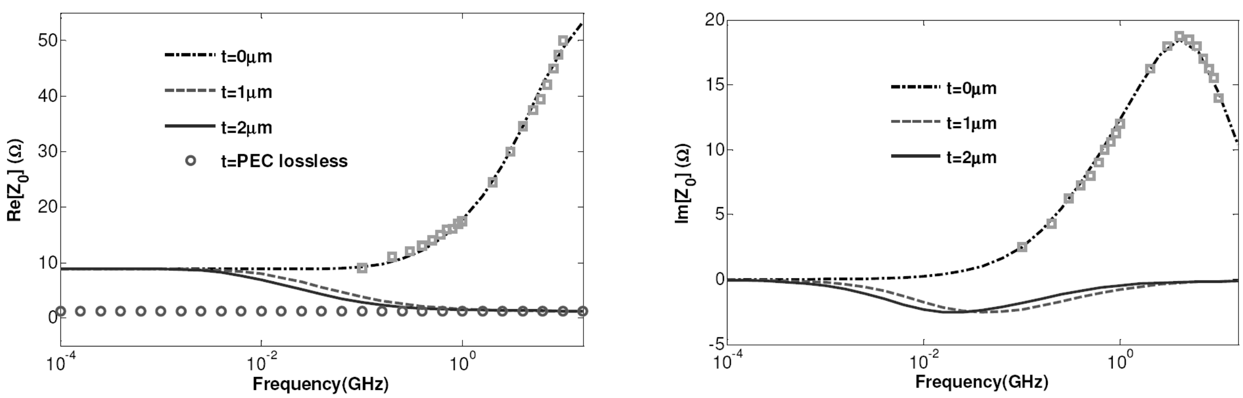
Here one modified case of MIS structure is considered with a thin metallic substrate inserted between the dielectric SiO_2 and lossy Si as shown in Figure 2(b). The ϵ_r of the silicon dioxide is 4 and its thickness is $1\,\mu$m. The width of strip is $160\,\mu$m. The thickness of the silicon layer is $250\,\mu$m with $\epsilon_r = 12$ and conductivity $\delta = 5\,$S/m. Figure 2 shows the frequency dependence of the attenuation constant and the normalized guiding wavelength, which is equivalent to the phase velocity normalized by the speed of the light in free space. When the t equals to zero, this modified structure is degraded into the typical metal-insulator-silicon structure previously studied by the Hasegawa et al. [5]. Our results agree well with the one calculated by Cano, Medina and Horno shown as rectangular dots in Figure 2. The further validation can be found in [7].

In Figure 2(a), as the frequency decreases, the normalized guiding wavelength converges to about 0.06. So the wave propagates on the microstrip lines much slower than in free space, which is known as the slow wave effect. In addition, several "limit" curves are marked. When the thickness of the middle metallic substrate grows to infinity, the effect of the silicon substrate and PEC ground underneath become negligible. Another curve is obtained by treating the middle metal as PEC to make the transmission system become lossless. This curve fits well with the result of Pramanick's and Bhartia's formula [8] shown as circle dots. With increasing the frequency, each curve with different thickness converges consequently to the critical curve representing the infinite metal thickness. This attributes to the fact that the skin depth decreases as the frequency increases. Physically it means the electromagnetic field experiences more attenuation when penetrating the same conductive metallic substrate. Thus at some points, the whole substrate can become opaque and block the field from reaching the lower substrate. At the high frequency, the thin metallic substrate will work as infinite thick metal ground, when the metal thickness equals to 2 to 3 times of the skin depth. For example, at 1 GHz, the skin depth of



(a) Normalized wavelength (b) Attenuation constant

Figure 2: Dispersion performance of a 3-layer MIMS open microstrip under different thicknesses t. (lower silicon thickness: $250\,\mu$m; ε_r: 12; σ: 5 S/m; thin metal σ: $5.8(10^7)$ S/m; upper silicon-dioxide: $1\,\mu$m, ε_r: 4; w: $160\,\mu$m; circle dots: Pramanick and Bhartia's results [8] for lossless microstrip lines; rectangular dots: Cano, Medina and Horno's results [6] for MIS structure).



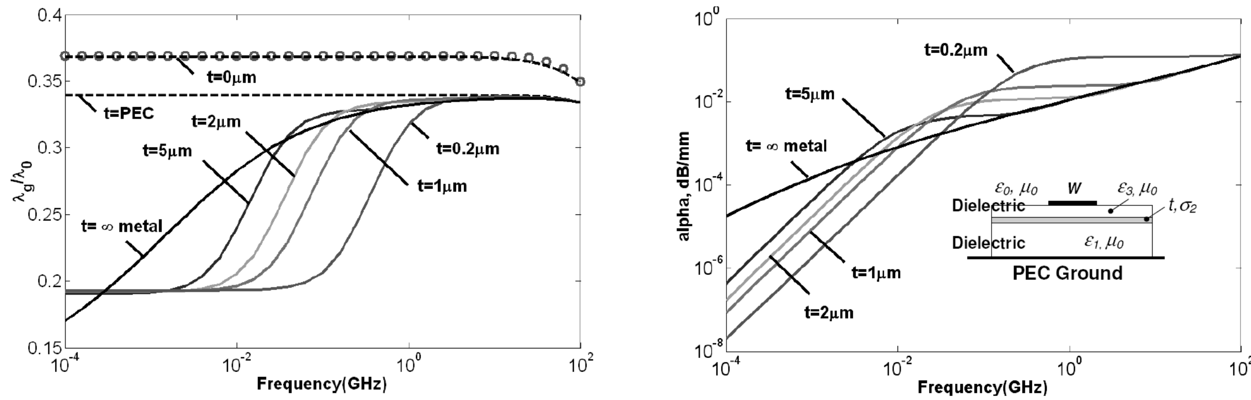
(a) Real part (b) Imaginary part

Figure 3: Frequency behavior of the (a) real and (b) imaginary parts of the characteristic impedance for the MIMS structure shown in Figure 2 (using $Z_0 = V/I$ definition, rectangular dots: Cano, Medina and Horno's results [6] for MIS structure).

copper is about $2\,\mu$m. The curve with thickness of $2\,\mu$m converges at around 4 GHz, almost 2 times thicker than the skin depth at 4 GHz. Similarly for $1\,\mu$m curve, the convergence point is about 25 GHz with skin depth $0.4\,\mu$m. In most of the frequency range shown, the normalized guiding wavelength decreases as the frequency decreases. When the skin depth is about 10 times more than the metal thickness, the wave becomes a slow wave.

Figure 2(b) also shows the behavior of the attenuation. The attenuation constants under different thickness of thin ground substrate approach consequently to the critical curve of infinite thickness. At the high frequency range, the attenuation is proportional to square root of the frequency. This is because the electric current flows through a region proportional the skin depth that is proportional to the inverse square root of the frequency. On the contrary, at the low frequency region, it is observed that the slopes of the curves are proportional to the square of the frequency, which is due to the ohmic loss of the electric current flowing in the metallic ground and substrate. In addition it is observed that the curves for finite thickness converge to the infinite thick metallic substrate when the thickness is equal to the skin depth. For example, the curve of $2\,\mu$m converges to the infinite thick at about 1 GHz. It shows that the concept of skin depth has more direct connection with the attenuation constant other than the phase velocity in Figure 2(a).

Figure 3 shows the relation of characteristic impedance versus frequency computed by using the definition of voltage-current. The voltage is defined as the path integral of the electrical field E_y on the y axis from the



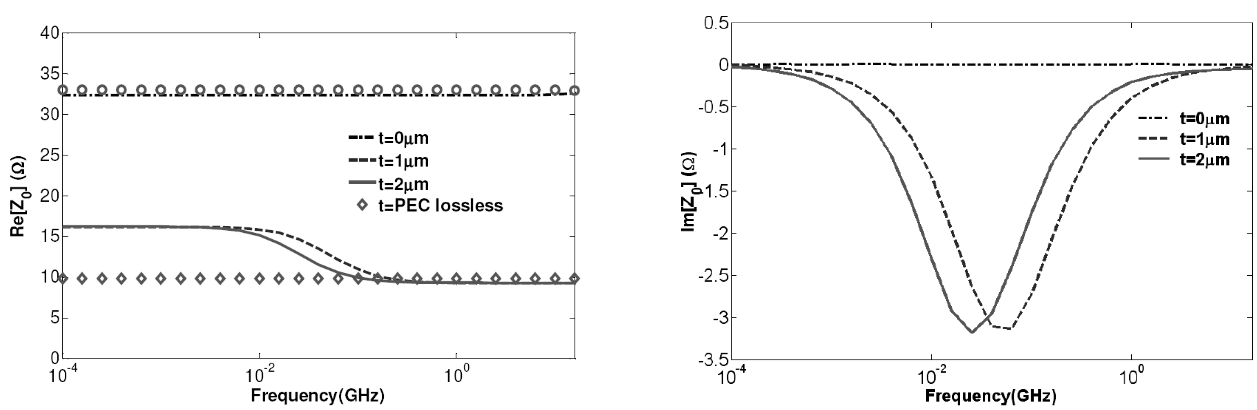
(a) Normalized wavelength (b) Attenuation constant

Figure 4: Dispersion performance of a 3-layer MIMI open microstrip under different thicknesses t of thin metallic substrate. (lower dielectric substrate: $80\,\mu$m; ε_r: 10.2; thin metal σ: $5.8(10^7)$ S/m; upper dielectric substrate: $20\,\mu$m, ε_r: 10.2; w: $200\,\mu$mm; circle dots: Pramanick et al. results [8] for lossless microstrip lines).

strip center to the ground plane and the current is the longitudinal current flowing through cross section of the strip. When the thickness t becomes zero, our result is validated by the result from Cano et al., [6] again. The figures show that when the thickness of the thin metallic substrate becomes larger, the characteristic impedance decreases. This behavior is very like the one when directly increasing the conductivity of silicon layer in MIS structure. The thicker this metallic substrate is, the more current flows through its cross section. Or equivalently, the impedance of this thin metal becomes smaller. When t becomes PEC, the impedance become pure resistance with the smallest value as shown (circle dots) in Figure 3(a).

3.2. Very Thin Metallic Substrate in Lossless System

As demonstrated before, the slow-wave is a comprehensive effect due to the influence coming from the lower lossy silicon substrate and this thin metal. To identify the influence of this thin metallic substrate only, a thin metal layer is inserted into a lossless microstrip line as shown in Figure 4(b). The lossless dielectric material ($\varepsilon_r = 10.2$) is divided into two parts as $20\,\mu$m and $80\,\mu$m. The width of the metal strip line is $200\,\mu$m. The corresponding dispersion characteristics are calculated and shown in the Figure 4(a) and 4(b). The similar patterns reoccur and accord with the previous figures and discussions. This also illustrates that the thin metal layer with finite conductivity in a lossless substrate can introduce the slow wave phenomenon at the low frequency range.



(a) Real part (b) Imaginary part

Figure 5: Frequency behavior of the (a) real and (b) imaginary parts of the characteristic impedance for the MIMI structure in Figure 4 (using $Z_0 = V/I$ definition, circle and diamond dots: Pramanick and Bhartia's results [8] for lossless microstrip lines with $100\,\mu$m and $20\,\mu$m dielectric substrates repectively).

In addition the remarkable difference between the PEC and real metal shows that the slow wave exists even when the thickness is only small fraction of the skin depth. This is a phenomenon that the PEC cannot describe appropriately. It is concluded that this thin metallic substrate has great impact on the dispersion characteristics of microstrip lines.

In Figure 5, the real and imaginary parts of the impedance are also plotted. when t equals to zero, our result agrees with the Pramanick's. The imaginary parts of the impedance is relatively small compared with the real parts. At the same time, when the metallic substrate becomes thicker, the impedance converges to the PEC (diamond dots in the figure) faster at the higher frequency range. This is because the reduction of the skin depth with increasing frequencies makes the thin metallic substrate more likely act as the good conductor with infinity thickness.

4. Conclusion

The effects of a thin metal ground with finite conductivity on the dispersion characteristics of loss and lossless multilayer microstrip line have been examined using the rigorous spectral domain approach. The numerical results show that electromagnetic field can penetrate the metal layer and interact with layers underneath. It is found that the thin metallic substrate in both lossy and lossless cases has a great impact on the dispersion characteristics, such the propagation constant, attenuation constant and characteristic impedance of multilayer microstrip lines even the thickness is much less than the skin depth. If considering the signal phase constant or velocity, the thin metallic substrate with thickness greater than 2 to 3 times of the skin depth can be regarded as infinite thick. At the same time, if merely the attenuation considered, the thin metal with only one skin-depth thickness is enough to make the ground like infinite thick. The results show that, at the low frequency range, the thin metallic substrate can excite a slow wave in both lossy and lossless multilayer microstrip lines.

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