A New Method for Locating the Poles of Green's Functions in a Lossless or Lossy Multilayered Medium

Dao-Xiang Wang, Edward Kai-Ning Yung, Ru-Shan Chen, *Member, IEEE*, and Jian Bao

***Abstract*—A new method is presented to locate the poles of the Green's functions for a general multilayered medium, whether lossy or lossless. The problem associated with the pole extraction is reduced to solve the contour integrals in the complex plane that are represented in terms of the spectral-domain transmission coefficients. With the help of Cauchy's theorem, the proposed method can accurately and rapidly find all surface wave poles with a few contour integrals. The numerical examples are performed to show the efficiency of the method.**

***Index Terms*—General multilayered media, Green's functions, surface wave poles.**

I. Introduction

INTEGRAL equations (IEs) have been widely employed for the modeling of microwave/millimeter-wave circuits and antennas based on multilayered media. Numerical solution of these IEs is usually achieved by using the spatial-domain method of moments (MoM). A critical requirement to apply the MoM is the evaluation of spatial-domain multilayered Green's functions, which are customarily expressed in terms of the Sommerfeld integrals (SI) [1]. The computation of the SIs is quite time-consuming and dominates the performance of the MoM solution because the integrated functions are strongly singular, slowly decaying and highly oscillatory. A method to alleviate this difficulty is adopting the divide-and-conquer strategy. Simply put, the poles of the integrals and the corresponding residues are extracted beforehand. Their contributions to the integrals are calculated separately while the remaining parts could be handled easily by using the complex image method (CIM) [2]. Therefore, the key point is finding the poles of the integrated functions, namely, surface wave poles for Green's functions.

Over the years, methods for locating the poles of Green's functions have been advanced frequently [3]–[8]. In [3], a method based on the residue theorem was proposed for the lossless multilayered media. In this method, the concerned interval will be recursively split into a number of sub-intervals, over which contour integrals are performed to check whether or not there are poles inside. This method does offer a useful way to locate the poles of multilayered Green's functions, but its accuracy heavily depends on the size of the smallest sub-interval. Although much smaller interval gives rise to higher accuracy, it will drastically increase the number of contour integrals and consequently becomes computationally expensive, particularly when the poles are in close proximity to the branch cuts. To reduce the number of contour integrals, another method was proposed in [4] by properly choosing a finite exponential series that is assumed to be a function of the poles and residues. Then, the poles are roughly approximated by using the generalized pencil-of-function (GPOF) method [5] and are further refined by applying a root-searching procedure such as the Newton-Raphson method. Unfortunately, the number of contour integrals is difficult to determine in advance and relies mostly on the experimental trials. Especially when there may exist two poles very adjacent to each other, this method will fail to pick up them. What's more, a common deficiency of the above two methods is that they are not sufficiently efficient for lossy multilayered media, notwithstanding an example has been presented in [6] to show the potentials of the second method in handling a single-layer dielectric slab having a small loss permittivity. Recently, the other two methods for locating the surface wave poles of lossy layered media have been developed in [7] and [8]. They both exhibit high accuracy and speed, but they restrict themselves on the single-layer lossy slab with the grounded planes, which are only a small part of practical applications.

The aim of this paper is to develop an accurate and fast method for locating the surface poles of Green's functions in the general multilayered media, whether lossless or lossy. With the aid of the residue theorem, the problem is first transformed to solve the contour integrals in the complex k_ρ-plane. In this way, the method will be not reliance on material properties and physical parameters of the media. For a given region that is assumed to be large enough to include all the poles, it is quite easy to check whether there are or not poles inside by

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performing only a contour integral. If the region includes one pole, we observe that it needs two contour integrals to calculate the pole by directly applying Cauchy theorem, instead of successively performing the contour integrals over much smaller sub-regions [3]. If the region possibly includes many poles, we split it into some sub-regions so that each sub-region includes one pole at most. This will be achieved by the use of limitation conditions as described in the following section. The details of the method will be elaborated in Section II, and then followed by numerical examples to demonstrate its efficiency.

II. Theory and Formulation

A. The Spectral-Domain Terms Including Poles

The theory on the derivation of the multilayered Green's functions has been well established in [1]. In common, the C Formulation is used more preferably since it eliminates extra line integrals in the spatial-domain MoM solution. Through a careful inspection, it will be found that the poles, either for the dyadic vector potential $\overleftrightarrow{\tilde{G}}^{\mathbf{A}}$ or for the scalar potential $\tilde{G}^{\Phi}$, are actually contained in some key terms, called spectral-domain transmission voltage and current coefficients, namely $\tilde{V}_i^{\mathrm{TM,TE}}$ and $\tilde{I}_i^{\mathrm{TM,TE}}$ (where $i = V$ or I) [9]. These spectral voltages and currents are complex rational functions whose denominators, for both TE and TM polarizations, are related to the dispersion equation of the multilayered structure. Thus, the problem is finding the poles of the voltage coefficients $\tilde{V}_i^{\mathrm{TM,TE}}$ (or current coefficients $\tilde{I}_i^{\mathrm{TM,TE}}$). Throughout this context, the spectral-domain voltage coefficients $\tilde{V}_I^{\mathrm{TM,TE}}$ is used, and denoted as

$$\tilde{V}_I^P = \frac{1}{D_n^P}\Big[\overleftarrow{\Gamma}_n^P \exp(-jk_{zn}\gamma_{n1}) - \overrightarrow{\Gamma}_n^P \exp(-jk_{zn}\gamma_{n2}) + \overrightarrow{\Gamma}_n^P\overleftarrow{\Gamma}_n^P \exp(-jk_{zn}\gamma_{n3}) - \overrightarrow{\Gamma}_n^P\overleftarrow{\Gamma}_n^P \exp(-jk_{zn}\gamma_{n4})\Big] \tag{1}$$

where p strands for TM or TE-type transmission line; $k_{z,i} = \pm\sqrt{k_i^2 - k_\rho^2}$ $(i = 0, 1, 2, \ldots)$ is the wavenumber along z-axis and its sign is determined by $\mathrm{Imag}(k_{z,i}) < 0$ to satisfy the radiation condition; k_ρ is transverse propagation wave constant.

$$\gamma_{n1} = 2z_{n-1} - (z + z') \tag{2}$$
$$\gamma_{n2} = (z + z') - 2z_n \tag{3}$$
$$\gamma_{n3} = 2d_n + (z - z') \tag{4}$$
$$\gamma_{n4} = 2d_n - (z - z') \tag{5}$$
$$D_n^p = 1 - \overrightarrow{\Gamma}_n^p \overleftarrow{\Gamma}_n^p e^{-j2k_{zn}d_n} \tag{6}$$
$$\overrightarrow{\Gamma}_n^p = \frac{\Gamma_{n-1,n}^p \overrightarrow{\Gamma}_{n-1}^P e^{-j2k_{z,n-1}(z_{n-2}-z_{n-1})}}{1 + \Gamma_{n-1,n}^p \overrightarrow{\Gamma}_{n-1}^P e^{-j2k_{z,n-1}(z_{n-2}-z_{n-1})}} \tag{7}$$
$$\overleftarrow{\Gamma}_n^p = \frac{\Gamma_{n+1,n}^p \overleftarrow{\Gamma}_{n+1}^P e^{-j2k_{z,n+1}(z_{n+1}-z_n)}}{1 + \Gamma_{n+1,n}^p \overleftarrow{\Gamma}_{n+1}^P e^{-j2k_{z,n-1}(z_{n+1}-z_n)}} \tag{8}$$
$$\Gamma_{ij}^p = \frac{Z_j^p - Z_i^p}{Z_j^p + Z_i^p}. \tag{9}$$

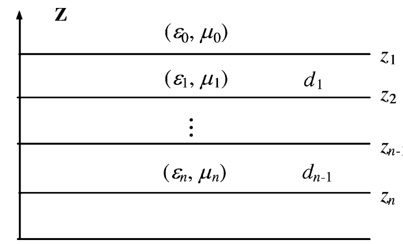


Fig. 1. Configuration of a general multilayered medium.

As shown in Fig. 1, $\Gamma_{m,n}^p$ is the Fresnel reflection coefficient looking from mth to nth layer; $\overrightarrow{\Gamma}_n^P$ and $\overleftarrow{\Gamma}_n^P$ are the generalized reflection coefficients looking upward (i.e., in the +z direction) and downward at the nth interface, respectively; Z_n^p is the TE or TM characteristic impedance inside the nth layer medium; z_n is the position of the nth interface and d_n is the thickness of the nth layer; z and z' are source and observation positions, respectively.

B. The Pole Extraction of Surface Waves

Before extracting the poles of $\tilde{V}_I^{\mathrm{TM,TE}}$, we begin with a brief description of a lemma that forms the basis of the pole extraction in our method.

Assuming that an analytic function $F(x)$ having a simple pole at $x = x_0$ within a simply connected domain Ω bounded by a Jordan curve C, one may derive the following identity in terms of Cauchy's integral theorem,

$$\oint_C xF(x)\,dx = x_0 \oint_C F(x)\,dx. \tag{10}$$

Obviously, the pole x_0 can be directly obtained by simple mathematic manipulation once two contour integrals in (10) are known. The pole obtained in such a manner will be highly accurate. It is because two contour integrals can be precisely calculated if an integration procedure is properly chosen. However, for the function $F(x)$ having more than one pole, the formulation (10) will fail to give the correct pole and the pole obtained by using (10) may be a spurious solution. In this case, the integration domain Ω needs be recursively divided into much smaller sub-domains as proposed in [3] until each sub-domain would contain at most one pole. To this end, the limitation conditions must be enforced in each sub-domain.

If a solution x_0 is obtained by using (10) for a sub-domain Ω_s bounded by C_s, it will be considered as a possible candidate. Then, for a given tolerance e, we shall have

$$\left|\oint_{C_{x_0 \pm e}} F(x)\,dx\right| > e \tag{11}$$

where the closed contour $C_{x_0 \pm e}$ is defined by a small circle $|x - x_0| = e$. If expression (11) is true, x_0 will be regarded to be one pole. Otherwise, the sub-domain Ω_s needs to be further divided into much smaller ones until (11) is satisfied. Therefore, the pole can always be found only if an appropriate tolerance e is carefully chosen. Since the absolute tolerance used in (11) may increase the precision requirement of an integration routine, one can verify x_0 by using the following conditions, alternatively

$$\left| \frac{\oint_{C_s} F(x)\,dx - \oint_{C_{x_0 \pm e}} F(x)\,dx}{\oint_{C_s} F(x)\,dx} \right| < e \tag{12}$$

or equivalently,

$$\left| \frac{\oint_{C_s} xF(x)\,dx - x_0 \oint_{C_{x_0 \pm e}} F(x)\,dx}{\oint_{C_s} xF(x)\,dx} \right| < e \tag{13}$$

The above two inequalities are associated with each other and either one of them can be mathematically deduced from another while x_0 is unique pole in Ω_s. However, thanks to the effects of numerical errors, they may sometimes not be satisfied simultaneously. For safety, these two conditions shall be used together to examine x_0 more strictly.

In our experiments, we find that condition (11) are very sensitive to round-off errors and may miss the solution at a time while conditions (12) and (13) work well at all times. This is partly because the absolute errors used in (11) is more sensitive to the integration procedure than the relative errors used in (12) and (13).

For ease of understanding, the algorithm is summarized as follows:

Step 1: Calculate the contour integral $\oint_{C_s} F(x)\,dx$. If its magnitude is smaller than the given tolerance, there is no pole within the enclosed domain and stop the searching procedure;

Step 2: Calculate the contour integral $\oint_{C_s} xF(x)\,dx$ and solve x_0 using (10);

Step 3: If x_0 does not fall in the sub-domain Ω_s, divide the sub-domain into much smaller ones and repeat from step 1. Otherwise, go to step 4;

Step 4: Verify x_0 using the conditions of (11), or (12) and (13). Repeat from step 1 for other sub-domains.

III. Numerical Results and Discussions

In this section, numerical examples are presented to demonstrate the accuracy and rapidity of the proposed method for locating the surface wave poles of multilayered Green's functions. All program codes according to the formulations in Section II are executed on a PC desktop computer with Intel Pentium® 4 CPU 1.86G. Since the integrated functions are usually not smooth, the adaptive Simpson quadrature method is adopted and a relative tolerance and an absolute tolerance are selected with of 10^{-4} and 10^{-8}, respectively.

First example considers a single-layer medium with the dielectric constant $\varepsilon_r = 4$, the thickness $h = 5$ mm and the operated frequency $f = 10$ GHz. This geometry is chosen because the corresponding Green's function includes a simple pole that is close to its branch cut at $k_\rho = k_0$ (k_0 is the free-space wave number) and is not easy to extract [3]. To apply the proposed method, the integral domain should be defined beforehand. It can be proven that for a lossless layered medium, the surface wave poles should locate in the range of $(0, \sqrt{\varepsilon_{r\,\max}}k_0)$ along the real k_ρ-axis (where $\varepsilon_{r\,\max}$ is the maximum dielectric constant). For this geometry, the explicit expressions of $V_I^{\mathrm{TE,TM}}$ can be derived analytically and the poles can be found using the Newton method. With our method, only three contour integrals are used to find all the poles for the given range and the overall CPU time is almost negligible. As listed in Table I. it is observed that the results obtained from our method are exactly identical with those from the Newton method.

TABLE I
TE and TM Wave Poles for a Single-Layer Lossless and Lossy Substrate

Pole (*rad/cm*)	Newton method (Lossless)	Our method (Lossless)	The method [6] ($\tan\delta = 0.02$)	Our method ($\tan\delta = 0.02$)
p_{TM}	3.261989	3.261989	3.2653-*j*0.0402	3.2620-*j*0.0401
p_{TE}	2.220789	2.220789	2.2226-*j*0.0238	2.2200-*j*0.0237

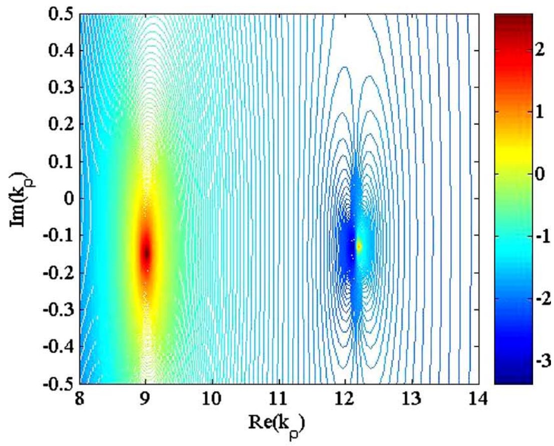
It is well known that the contribution of surface wave poles is dominant in the far-field region for a lossless medium while they are also main parts within a certain range for a lossy medium, and hence, must be carefully accounted for. For the first example, the dielectric slab is assumed to be lossy and $\tan\delta = 0.02$. In this case, the real and imagine part of the poles will be within the range of $(0, \max\{\mathrm{real}(k_n)\})$ and $(\min\{\mathrm{imag}(k_n)\}, 0)$, respectively (where k_n defines the complex wave number of the n th layer medium). It is not difficult to prove that the results will be less significant in physics beyond this range. Finally, our method uses only three contour integrals to find all surface wave poles and the results are also well compared with those by the method [6] as listed in Table I. It is not surprising to see that the poles move away from the real axis into the fourth quadrant because they have to satisfy the radiation boundary condition. As the operated frequency is changed to be $f = 30$ GHz, there are possibly more poles in the given range. Therefore, the limitation conditions of (11)–(13) need to be used simultaneously to guarantee that no pole is missed in the searching process. Finally, four poles are captured successfully with sixteen contour integrals totally and the CPU time is even less than 0.02 seconds. The results are as follows:

$$p^{\mathrm{TM}} : \{0.0012 - j0.1467, 12.2040 - j0.1282\} \quad (\mathrm{rad/cm}) \tag{14}$$

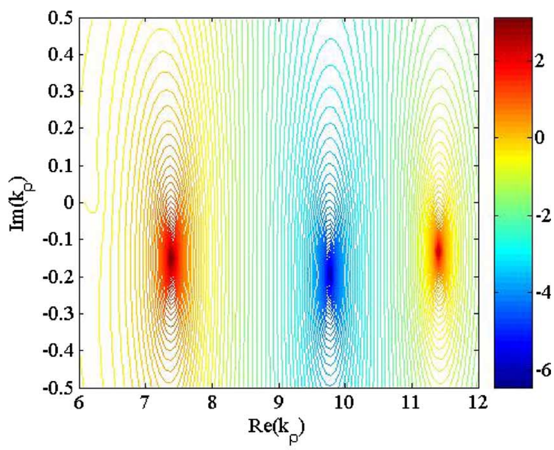
$$p^{\mathrm{TE}} : \{7.3966 - j0.1506, 11.4078 - j0.1328\} \quad (\mathrm{rad/cm}) \tag{15}$$

To further verify the poles obtained by our method, we plot behavior of the characteristic function $10\log_{10}|V_v^{\mathrm{TM,TE}}$ in the complex k_ρ-plane as shown in Figs. 2(a) and (b) where the value of the functions at the poles are usually corresponding to the position of the peak. It is clearly displayed that the poles for TE and TM waves are in good agreement with those by our method.

To demonstrate the efficiency of the proposed method for the general multilayered media, a five-layer medium with a PEC ground plane is analyzed [6]. The geometrical dimension and dielectric parameters are shown in Fig. 3. As the operated frequency $f = 30$ GHz, our method needs to calculate only sixteen



(a)



(b)

Fig. 2. (a) Distribution of TM wave poles normalized by k_0 for a two-layer loss medium with $\tan\delta = 0.02$. The poles locate at $(9.0012 - j0.1467)$ and $(12.2040 - j0.1282)$. (b) Distribution of TE poles normalized by k_0 for a two-layer loss medium with $\tan\delta = 0.02$. The poles locate at $(7.3966 - j0.1506)$ and $(11.4078 - j0.1328)$.

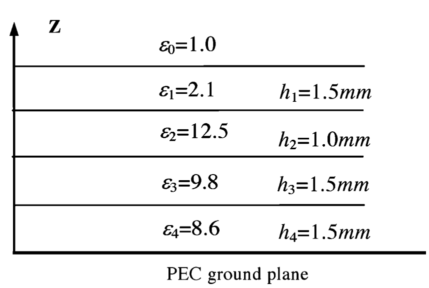
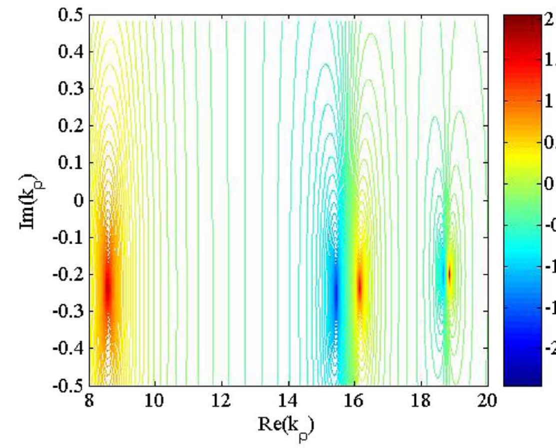
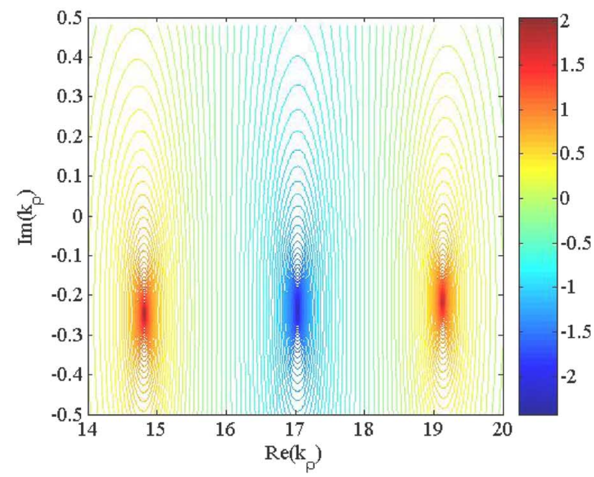


Fig. 3. Configuration of a five-layer medium.



(a)



(b)

Fig. 4. (a) Distribution of TM wave poles normalized by k_0 for a five-layer loss medium with $\tan\delta = 0.02$. (b) Distribution of TE wave poles normalized by k_0 for a five-layer loss medium with $\tan\delta = 0.02$.

TABLE II
TE AND TM WAVE POLES FOR A FIVE-LAYER LOSSLESS AND LOSSY SUBSTRATE

Pole (*rad/cm*)	The method [6]	Our method		
	Lossless case	Lossless case	Lossy case ($\tan\delta = 0.02$)	Lossy case ($\tan\delta = 0.2$)
p_{TM}	8.6019	8.5844	8.5787-*j*0.2364	7.8894-*j*2.7340
	16.1638	16.1478	16.1494-*j*0.2329	16.3122-*j*2.3076
	18.8630	18.8498	18.8507-*j*0.2002	18.9407-*j*1.9917
p_{TE}	6.2893	6.2841	—	—
	14.8323	14.8151	14.8170-*j*0.2484	14.9927-*j*2.4607
	19.1407	19.1259	19.1270-*j*0.2151	19.2322-*j*2.1396

and twelve contour integrals for TM and TE wave poles, respectively and the whole CPU time is approximately 0.03 seconds. All the poles obtained by our method are listed in Table II, and are found to be well consistent with the existing data [6]. When a loss tangent $\tan\delta = 0.02$ or 0.2 is specified for each bounded layer, all the poles are also captured successfully as given in Table II. To confirm that no pole is missed, the characteristic functions $10\log_{10}|V_v^{\mathrm{TM,TE}}$ are plotted in Figs. 4(a) and (b). We can observe that all the poles corresponding to the peak of the function are in good agreement to those by our method. Although a bit more contour integrals are calculated, the needed CPU time is less than 0.08 seconds.

As a further check to the efficiency of our method, we also examine this example for the different frequencies. Table III summarizes the results, indicating that the proposed method needs

TABLE III
THE CPU TIMES VERSUS THE NUMBER OF POLES

Frequency (GHz)	Pole Number		CPU time (sec.)
	TM	TE	
20	2	2	0.015
40	4	3	0.031
60	6	6	0.094
80	8	7	0.109
100	10	9	0.203

less CPU time to find all the poles of the multilayered Green's functions. For comparison, the distribution of the characteristic functions are also plotted to show the location of these poles and not shown here for the limited space.

IV. CONCLUSION

A new method has been developed in this paper for automatic extraction of the surface wave poles of multilayered Green's functions. Both lossless and lossy media have been considered. Pole solutions that are resulted from the spectral-domain transmission voltage/current coefficients can be easily accomplished in a few seconds by using the proposed method. Through the examples considered, the accuracy and rapidity of the method are demonstrated. Although the contour integral is required, the method is not reliance on the physical geometry, material properties or operated frequency, and therefore, is very useful for evaluating spatial-domain Green's functions of a general multilayered medium.

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