A new algorithm for the extraction of the surface waves for the Green’s function in layered dielectrics

SONG Ben (宋 铫) & HONG Wei (洪 伟)

State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China
Correspondence should be addressed to Hong Wei (email: weihong@seu.edu.cn)

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Abstract There exist the complicated waveguide modes as well as the surface waves in the electromagnetic field induced by a horizontal electric dipole in layered lossless dielectrics between two ground planes. In spectral domain, all these modes can be characterized by the rational parts with the real poles of the vector and scalar potentials. The accurate extraction of these modes plays an important role in the evaluation of the Green’s function in spatial domain. In this paper, a new algorithm based on rational approximation is presented, which can accurately extract all the real poles and the residues of each pole simultaneously. Thus, we can get all the surface wave modes and waveguide modes, which is of great help to the calculation of the spatial domain Green’s function. The numerical results demonstrated the accuracy and efficiency of the proposed method.

Keywords: Green’s function, surface waves, layered dielectrics, rational approximation.

Among a variety of methods developed for electromagnetic modeling of Microwave Integrated Circuit (MIC), the incorporation of the spatial-domain method of moment (MoM) in the mixed potential integral equation (MPIE) formulation is a general and rigorous one[1]. The core of the technique is the calculation of the spatial-domain Green’s function, since one has to take care of the Sommerfeld integral (SI), which involves a highly oscillatory and slowly decaying kernel, the zeroth-order Bessel function of the first kind. Many contributions have been made to this integral[2-7]. They fall into two categories. In the first or direct integration approach, the integration path can be the real axis[2] or a deformed path on the complex plane[3]. In a real-axis integration scheme, singularities of the integrand should be found out and removed first via the residue calculus. As for the deformed path integration, the associated Bessel function with complex arguments may cause difficulty in obtaining accurate results. Recently, the fast Hankel transformation (FHT) algorithm is proposed to accelerate the real-axis integration scheme for the calculation of the spatial-domain Green’s function[7].

The second category is an (asymptotic) approximation of the SI, more specifically referred to as the complex-image method (CIM)[4-6]. Only a few closed-form complex images (images with complex amplitudes and locations) are required to approximate the SI over a moderate distance range[6]. The two-level approach can make the choice of the numbers of complex images and sampling points and the endpoints of the sampling regions robust, so it provides accurate representation of the Green’s function and is much faster compared to the original one-level approximation[6].

In order to reduce the radiation and coupling, the microwave circuits are often enclosed in
metal boxes. For the same reason, MICs usually also have metal packages. The commonly used model for the analysis of the boxed circuits ignore the side walls, that is to say, only a layered structure between the two ground planes is considered. Since the loss tangent of the widely used materials in microwave circuit are so small that the loss of the material can be ignored, the model involved in this paper is lossless layered dielectric between the two ground planes.

The surface wave modes are the inherent propagation modes trapped by the layered dielectric. There are two types of surface wave modes, the LSE mode and the LSM mode. They can exist even without the strips and propagate along the interface between two different layers. Since they attenuate slowly in propagation, the surface waves dominate the long source-observe range. Because the existence of two ground planes, there exist the waveguide modes of both LSE and LSM types as well in a shielded layered structure\[5\]. In spectral domain, all the propagating modes of these two kinds can be characterized by the rational parts with the poles on the real axis. They only differ in the facts that all the poles of the propagating surface waves are located in the interval \([k_0, \varepsilon_{\text{max}}k_0]\), while all the poles of propagating waveguide modes are located in the interval \([0, k_0]\). Here, \(k_0\) is the wavenumber of free space. Because both the surface waves and the waveguide modes attenuate slowly, they dominate the far field together.

The accurate extraction of surface waves and wave-guide modes plays an important role in the evaluation of the Green’s function in the spatial domain. After the analytic extraction of these modes, the remainder of the spectral-domain Green’s function is smooth on the real axis, which can facilitate the numerical integration along the real axis. At the same time, the smoothed integrand is also ready for the acceleration techniques such as FHT\[7\]. Even in the approximation approach such as complex-images method (CIM), the pre-extraction of the surface wave and waveguide modes is also helpful, because it can improve the approximation efficiency and provide a more precise characterization for the far field. Recently, Fang et al.\[8,9\] even indicated that the extraction of surface waves is a prerequisite for the CIM when applied to the 2D cases.

Because of the complexity of the spectral-domain Green’s function in layered medium, it is tough to accurately determine all the poles on the real axis and their residues. To the best of the authors’ knowledge, the published methods for the extraction of surface waves are all based on the root-search like algorithms, such as the bisection method, the Muller’s method and the Davidenko’s method\[8\]. They determine the positions of poles first by searching for all the poles of a transcendental equation, then integrate along the contour around each pole to acquire its residue via the Cauchy’s residue theorem. The shortcomings of these methods are: the bisection method needs more computation and is subject to missing roots; the Muller’s method is strongly dependent on the initial guess and an improper initial guess will lead to divergence; since the Davidenko’s method is less sensitive to the initial guess, it requires the use of the denominator of the spectral domain Green’s function and its derivative explicitly. It is also troublesome when multiple roots are present. The counts of real-axis poles of the spectral-domain Green’s function for the layered medium will increase with the rise of the operation frequency, which will certainly make it a great challenge for the above surface-wave extraction methods to accurately find all the poles and their residues with high efficiency.

In this paper, a new surface-wave extraction algorithm based on the rational approximation is presented for the layered lossless medium between two ground planes. The proposed algorithm can