Figure 5 Measured antenna gain for the proposed and reference antennas

here all have a circular shape, it is expected that the proposed design can be applied to a rectangular or square wide-slot antenna with rectangular or square tuning stub, and similar band-notched UWB operation can be obtained.

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A HYBRID FAST CONVERGING SERIES EXPANSION FOR THE 2D GREEN'S FUNCTION OF A MULTILAYERED MEDIUM

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ABSTRACT: A new formalism combining modal expansions based on perfectly matched layers (PMLs) and on Floquet modes is proposed to derive a fast-converging series expansion for the 2D Green's function of layered media. The PML-based modal expansion is obtained by terminating the waveguide, formed by the layered medium, with PMLs. The convergence of this series is improved by adding an expansion of Floquet modes corresponding to an auxiliary periodic problem. The period

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of this auxiliary problem acts as a parameter, the convergence rate of both series allowing to be controlled. The formalism is applied to a dielectric-slab waveguide to illustrate the improved convergence and the efficiency of the new approach. © 2005 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 45: 130–134, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20747

Key words: integral-equation techniques; Green's functions for multilayered media; perfectly matched layers

1. INTRODUCTION

The efficient evaluation of the Green's functions in a multilayered medium is of major importance when modelling planar antennas and microwave circuits by means of integral-equation descriptions [7, 14, 20]. The classical approach [8, 13] relies on calculating the Green's functions first in the spectral domain and then applying an inverse Fourier transform for the 2D case, or an inverse Hankel transform for the 3D case. The latter transformation results in Sommerfeld-type integrals, requiring complex and time-consuming integration schemes. Therefore, a number of faster alternative approaches have been proposed, such as, for example, the fast Hankel transform [10] and the complex image technique [4, 21]. In [2, 5, 6], a new technique was proposed to calculate the Green's function by using perfectly matched layers (PMLs) [1, 3, 9, 11] to obtain a closed-waveguide configuration. The PML then mimics an open structure, while an efficient problem description in terms of a set of discrete modes of the closed waveguide containing the PMLs is possible. It is clear that the efficiency of this technique depends on the convergence rate of the modal series. For a 2D waveguide, consisting of the multilayered medium terminated with PMLs backed by perfectly electric conducting (PEC) planes, as shown in Figure 1, it is shown in [16] that the modal series corresponding to the Green's functions (that is, to a line-source excitation in the multilayered medium) converge exponentially whenever the excitation and observation points are well separated in the lateral direction (the distance is taken along the waveguide axis). For small lateral separations, the exponential convergence is lost, and the series either converges very slowly or diverges. For small transverse separations (the distance is taken to be perpendicular to the waveguide axis), this is not surprising, as the Green's function becomes singular when the observation point

Figure 1 Application regions for a different PML-based formalism: region bounded by the dashed line: region of exponential convergence for the conventional PML series; region bounded by the dotted-dashed line: region of exponential convergence for the new hybrid Floquet-PML-based series

approaches the excitation point. For these very near interactions, the classical rigorous approach is in order. However, for reasons of efficiency, one wants to avoid using the classical approach for all other interactions. In [16], it is demonstrated that the modal series either slowly converge or diverge for small lateral separations and both for small and large transverse separations of observation and excitation points, so that the use of the series for the latter interactions is rather impractical.

In this paper, we present a new modal series which exhibits exponential convergence specifically for these interactions with a small lateral separation and a large transverse separation between the source and observation points (Fig. 1). The new formalism combines the modal expansion based on PMLs with a series of Floquet modes. The expansion in Floquet modes represents the Green's function of an auxiliary periodic problem. The period of this auxiliary problem acts as a parameter allowing the convergence rate of both series to be controlled. By increasing the period, the convergence rate of the PML-based modal expansion is improved at the expense of the convergence rate of the Floquet-mode series. By decreasing the period, the convergence rate of the Floquet-mode series increases whereas the convergence rate of the PML-based modal expansion decreases. A suitable choice for the period guarantees exponential convergence for both series in that region where the classical PML-based modal expansion of the Green's function loses convergence. Therefore, the new series supplements the existing PML-based series and increases the overall efficiency of the Green's function evaluation in multilayered media.

2. GENERAL THEORY

Consider a planar stratified medium, consisting of several dielectric layers. The configuration is translation invariant in the y direction (a planar stratified medium). The material parameters may vary along the z direction, but only within a bounded region. The largest distance over which material variations extend in the z direction is denoted by t (Fig. 1). We are interested in determining the Green's function corresponding to a line source located in the stratified medium. As in [2, 5, 6, 15, 17], a faster evaluation of the 2D Green's function is obtained if we construct a parallel-plate waveguide by terminating the homogeneous layers at the top and bottom of the stratified medium with two PEC plates backed by a PML of thickness d_{PML} and having material parameters κ_0 and σ_0 [5], as shown in Figure 1. Of course, formalism also applies to a planar stratified medium above a ground plane. In that case, a single PML is used to convert the open configuration into a closed waveguide. For both configurations, the Green's function for the closed waveguide can then be written as a series of discrete modes, as follows:

$$G_{xx}(y, z|y', z') = \sum_{m=-\infty}^{\infty} A_m(\beta_m, z|z') e^{-j\beta_m|y-y'|}, \quad (1)$$

where β_m denotes the eigenvalues and $A_m(\beta_m, z|z')$ denotes the excitation coefficients of the eigenmodes. In [16], it is shown that this modal series converges exponentially whenever the excitation and observation points are well separated in the lateral direction, that is, for large lateral distances $|y - y'|$, independent of the transversal distances $|z - z'|$. However, the series becomes slowly convergent or diverges for small distances $|y - y'|$, independent of the transversal distances $|z - z'|$. Let us now derive a new series which exhibits exponential convergence for large distances

Figure 2 Calculation of the Green's function in a dielectric slab

$|z - z'|$, independent of the separation along the waveguide axis $|y - y'|$.

We start by first determining the Green's function for a periodic configuration of line sources, which is obtained by periodically extending the source under study by a period d , as shown in Figure 2. In [18], a PML-based formalism was applied and the following series was obtained for the periodic Green's function within the region $0 < y - y' < d$:

$$G_{xx}^{\text{per}}(y, z|y', z') = \sum_{m=-\infty}^{\infty} A_m(\beta_m, z|z') \left[e^{+j(\beta_m(y-y'))} \frac{e^{-j(\beta_m+k_y)(l+1)d}}{1 - e^{-j(\beta_m+k_y)d}} + e^{-j(\beta_m(y-y'))} \frac{e^{-j(\beta_m-k_y)(l+1)d}}{1 - e^{-j(\beta_m-k_y)d}} \right] + \sum_{n=-l}^l G_{xx}(y, z|y' + nd, z') e^{-jnk_y d}, \quad (2)$$

where $G_{xx}(y, z|y', z')$ is the nonperiodic Green's function of the multilayered substrate, k_y represents an imposed phase variation along the y axis, and l is an arbitrary parameter. By choosing $l = 0$, we can express the nonperiodic Green's function $G_{xx}(y, z|y', z')$ of the multilayered substrate in terms of the periodic Green's function, to be corrected by a PML-based modal series:

$$G_{xx}(y, z|y', z') = G_{xx}^{\text{per}}(y, z|y', z') - \sum_{m=-\infty}^{\infty} A_m(\beta_m, z|z') \times \left[e^{+j(\beta_m(y-y'))} \frac{e^{-j(\beta_m+k_y)d}}{1 - e^{-j(\beta_m+k_y)d}} + e^{-j(\beta_m(y-y'))} \frac{e^{-j(\beta_m-k_y)d}}{1 - e^{-j(\beta_m-k_y)d}} \right]. \quad (3)$$

Now, the second series contains an additional factor $e^{-j(\beta_m \pm k_y)d}$ which provides exponential convergence, even when $|y - y'| = 0$. The 2D periodic Green's function can, of course, be expressed in terms of the Green's function $G_{xx}(y, z|y', z')$, by following series expansion:

$$G_{xx}^{\text{per}}(y, z|y', z') = \sum_{n=-\infty}^{\infty} G_{xx}(y, z|y' + nd, z') e^{-jnk_y d}. \quad (4)$$

Since the background medium is translation invariant in the y direction, one can apply the Poisson transform [12] to find the series expansion over the Floquet modes:

$$G_{xx}^{\text{per}}(y, z|y', z') = \frac{1}{d} \sum_{n=-\infty}^{\infty} \tilde{G}_{xx}\left(y - y', z \left| \frac{2n\pi}{d} - k_y, z' \right. \right), \quad (5)$$

where $\tilde{G}_{xx}(y - y', z|\beta, z')$ is the Green's function in the spectral β -domain. This spectral-domain Green's function is easily determined, as shown in [8, 13]. Moreover, the series expansion (5) converges exponentially when the distance $|z - z'|$ becomes sufficiently large. Thus, in the region where $|y - y'|$ is small and where $|z - z'|$ becomes significant, one can apply the following series expansion:

$$G_{xx}(y, z|y', z') = \frac{1}{d} \sum_{n=-\infty}^{\infty} \tilde{G}_{xx}\left(y - y', z \left| \frac{2n\pi}{d} - k_y, z' \right. \right) - \sum_{m=-\infty}^{\infty} A_m(\beta_m, z|z') \left[e^{+j(\beta_m(y-y'))} \frac{e^{-j(\beta_m+k_y)d}}{1 - e^{-j(\beta_m+k_y)d}} + e^{-j(\beta_m(y-y'))} \frac{e^{-j(\beta_m-k_y)d}}{1 - e^{-j(\beta_m-k_y)d}} \right] \quad (6)$$

$$G_{xx}^{\text{per}}(y, z|y', z') = \frac{-j\omega\mu_0\mu_1}{d} \sum_{n=-\infty}^{\infty} \frac{e^{j((2n\pi/d)-k_y)(y-y')}}{\Gamma_1[(\mu_1^2\Gamma_2^2 + \mu_2^2\Gamma_1^2)\sinh(\Gamma_1 d) + 2\mu_1\mu_2\Gamma_1\Gamma_2\cosh(\Gamma_1 d)]} \begin{cases} \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(\frac{t}{2}-z'\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(\frac{t}{2}-z'\right)\right] \right) \cdot \mu_2\Gamma_1 e^{\Gamma_2|z+(t/2)|}, & z < -\frac{t}{2}, \\ \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(z+\frac{t}{2}\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(z+\frac{t}{2}\right)\right] \right) \cdot \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(\frac{t}{2}-z'\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(\frac{t}{2}-z'\right)\right] \right), & -\frac{t}{2} < z < z' < \frac{t}{2}, \\ \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(z'+\frac{t}{2}\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(z'+\frac{t}{2}\right)\right] \right) \cdot \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(\frac{t}{2}-z\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(\frac{t}{2}-z\right)\right] \right), & -\frac{t}{2} < z' < z < \frac{t}{2}, \\ \left(\mu_1\Gamma_2\sinh\left[\Gamma_1\left(z'+\frac{t}{2}\right)\right] + \mu_2\Gamma_1\cosh\left[\Gamma_1\left(z'+\frac{t}{2}\right)\right] \right) \cdot \mu_2\Gamma_1 e^{-\Gamma_2|z-(t/2)|}, & z > \frac{t}{2}, \end{cases} \quad (7)$$

with $\Gamma_1 = \sqrt{((2n\pi/d) - k_y)^2 - k_0^2\epsilon_r}$ and $\Gamma_2 = \sqrt{((2n\pi/d) - k_y)^2 - k_0^2}$. For large values of n , the terms of the series are proportional to $e^{-(2n\pi/d)|z-z'|}$, thereby guaranteeing an exponential convergence for $|z - z'|$ that is sufficiently large.

Let us now consider a dielectric slab with thickness $t = 18$ mm and permittivity $\epsilon_r = 3.0$. The PMLs are placed at a distance $d_{\text{air}} = 5$ mm from the slab and their characteristics are chosen to be $d_{\text{PML}} = 3.5$ mm, $\kappa_0 = 15$, $\sigma_0/\omega\epsilon_0 = 10$, at a free-space wavelength $\lambda = 20$ mm. Let us consider a line source lying in a dielectric slab at the location $y' = 0$ and $z' = 5$ mm (with the origin of the z axis located in the middle of the dielectric slab, as in Fig. 2). In a first experiment, we evaluate the Green's function along the line $y = 0$. Figure 3 shows the real part and Figure 4 shows the imaginary part of the Green's function $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$, comparing the conventional spectral-domain approach (without PMLs) with the new Floquet-PML-based formalism and the standard PML-based modal expansion. With regard to the parameters of the virtual periodic problem, we chose the period to be $d = 20$ mm and $k_y = 0$. For both the Floquet-PML-based formalism and the standard PML-based expansion, the Shanks transform is used to accelerate convergence of all the series, as discussed in [16]. It is seen that the results of the new Floquet-

in order to speed up the evaluation of the Green's function. The convergence rate of both series can be controlled by a suitable choice of the parameters d (the period of the auxiliary periodic problem) and k_y .

3. APPLICATION TO THE GREEN'S FUNCTION IN A DIELECTRIC SLAB

The new technique described in section 2 can, for example, be applied to determine the Green's function $G_{xx}(y, z|y', z')$ for a line source embedded in a dielectric slab, as shown in Figure 2. For reasons of simplicity, we assume that the line source carries an x -directed current, but the formalism of section 2 also holds for the other current orientations. In order to apply the PML formalism, the slab together with the array of sources is surrounded by two PMLs backed by PEC plates. In order to apply the series expansion (6), we first calculate the propagation constants of the eigenmodes for the waveguide formed by the slab together with the PML, using the fast formalism described in [19]. The coefficients $A_n(\beta_n, z|z')$ are then obtained by applying the techniques described in [5, 6, 16]. For the dielectric slab, the Floquet-mode expansion (5) for a line source lying in the slab $-(t/2) < z' < (t/2)$ and for $0 < y - y' < d$ is given by

PML-based modal series are in excellent agreement with those obtained using the conventional approach. On the other hand, it is clearly seen that the standard PML-based modal expansion experiences convergence problems for a wide range of z values. Furthermore, the new approach provides a significant speed-up, since

Figure 3 Real part of the Green's function $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$

Figure 4 Imaginary part of the Green's function $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$

the new Floquet-PML-based formalism takes 0.36 s of CPU time on a 2.4-GHz Pentium IV, where the conventional approach requires 4 s of CPU time and the standard PML technique needs 8 s to evaluate $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$ for the different z values. In Figure 5, the total number of modal terms required to guarantee convergence for $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$ is shown as a function of z . For the standard PML approach, this number stands for the terms in the series of leaky and Berenger modes, whereas for the Floquet-PML-based formalism, this number stands for the number of terms needed in the series of Floquet modes, as well as in the series of leaky and Berenger modes. The evaluation of the Green's function via the new Floquet-PML-based formalism clearly requires far less terms to obtain convergence, as compared to the standard PML approach. In order to make a judicious choice so as to assure convergence for the new Floquet-PML-based formalism, one can choose the period such that the exponential attenuation of the series of Floquet modes equals the exponential attenuation of the series of leaky and Berenger modes. An approximate analysis leads to the following rule of thumb for the period d :

$$d = \frac{|y - y'|}{2} + \sqrt{\frac{|y - y'|^2}{4} + \frac{2|z - z'| \left[(d_{\text{air}} + d_{\text{PML}}\kappa_0)^2 + \left(d_{\text{PML}} \frac{\sigma_0}{\omega \epsilon_0} \right)^2 \right]}{d_{\text{air}} + d_{\text{PML}}\kappa_0}} \quad (8)$$

Figure 5 Number of modal terms required to guarantee convergence for $G_{xx}(0 \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})$

Figure 6 Evaluation of $|G_{xx}(y \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})|$ using the mixed Floquet-PML-based formalism

When applying this rule, however, it is important to note that the series of Floquet modes represents an exact description of the periodic problem, whereas the accuracy of the series of leaky and Berenger modes depends on the absorption characteristics of the PML layer. As the accuracy of the latter series deteriorates for large values of the period d , we limit the maximum value of the period to two wavelengths. Figure 5 shows that the additional gain in convergence by the use of Eq. (8), compared to choosing a fixed period d , is rather limited. A substantial gain in convergence is seen only for very small values of $|z - z'|$. For all other values, the choice of the parameter d is not so critical. When applying the rule of thumb given by Eq. (8), the CPU time for the scenario studied in Figures 3, 4, and 5 drops to 0.24 s. It is clear that the gain in CPU time is marginal, compared to the case where the period d is assumed to be fixed at $d = 20 \text{ mm}$.

In Figure 6, the Green's function is evaluated in the region $-10 \text{ mm} \leq y \leq 10 \text{ mm}$ and $-39 \text{ mm} \leq z \leq 20 \text{ mm}$, by means of the mixed Floquet-PML-based formalism, and in Figure 7, by means of the conventional PML-based formalism. For the mixed Floquet-PML-based formalism, we chose the period to be fixed at $d = 20 \text{ mm}$. The evaluation of the Green's function in this region takes less than 2 s using the Floquet-PML-based formalism, whereas 18 s are required using the conventional PML-based formalism and 38 s using the classical spectral-domain approach. Moreover, as seen in Figure 6, the new formalism yields accurate results in the complete region, whereas the PML-based formalism suffers

Figure 7 Evaluation of $|G_{xx}(y \text{ mm}, z|0 \text{ mm}, 5 \text{ mm})|$ using the PML-based formalism

from divergence problems (Fig. 7), especially for small values of y .

4. CONCLUSION

A new formalism combining modal expansions based on PMLs and Floquet modes has been proposed to derive a fast-converging series expansion for the 2D Green's function of layered media. The new series expansion provides an accurate and efficient description for the Green's function of the multilayered substrate in these regions where the conventional PML-based series is known to converge poorly or diverge. It was shown that the convergence rate of both parts of the Green's function expansion (that is, the PML-based series and the Floquet series) can be controlled by an appropriate choice of the period d and the wave number k_y , corresponding to the auxiliary problem. Although a judicious choice clearly improves the efficiency even further, it was shown that the choice of parameters is not very critical in order to obtain significant speed-ups, as compared to the classical spectral-domain method and to the conventional PML-based approach.

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WAVELENGTH CONVERSION IN TAPERED-WAVEGUIDE LASER DIODE AMPLIFIERS

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ABSTRACT: Wavelength conversion using cross-gain modulation (XGM) in linear tapered-waveguide semiconductor laser amplifiers (SLAs) has been investigated theoretically and compared with the nontapered semiconductor laser amplifier. For example, we have found that for the linear tapered-waveguide SLA with a 450- μm cavity length, a higher signal power is required to achieve an extinction ratio similar to that obtained by the conventional SLA with the same cavity length. However, a similar extinction ratio is observed for both conventional and linear tapered-waveguide with the cavity length of 1200 μm . The difference between the extinction ratios for up and down conversions is less severe in a linear tapered-waveguide SLA as compared to that for a conventional SLA. The rise time for the linear tapered-waveguide is observed to be higher than that for the conventional SLA. It is possible to attain extinction-ratio conservation using XGM for both up and down conversions in an SLA with a very long cavity length of 2400 μm . © 2005 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 45: 134–142, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20748

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