NEAR AND FAR FIELD CHARACTERIZATION OF RADIATION FROM ULTRA-FAST ELECTRONIC SYSTEMS

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Abstract— **A numerical technique combining the FDTD method with a spatial transformation technique, the Kirchhoff surface integral, is proposed for determination of near and far field radiation from microwave, millimeter wave, or ultra-fast electronic systems. This technique is shown to be extremely accurate, and is often more computationally expedient than use of the FDTD alone. The technique is applied to characterize radiation from structures with inhomogeneous material parameters, offering a more accurate portrait of radiative fields than has been previously reported.**

Introduction

Radiation from microwave, millimeter wave, and ultra-fast electronic systems can be difficult to characterize for a variety of reasons. In general, the radiative source is distributed in nature relative to the wavelength of excitation and may originate from an entire component or region of a component. A variety of material parameters may be involved as well, which can significantly increase the complexity of the model. In pulsed millimeter wave and ultra-fast electronic systems, the radiation is often wideband, generally precluding the use of frequency domain techniques. Many of these difficulties can be alleviated through the use of a time domain technique such as the FDTD [1], [2]. However, at very high frequencies, the computational domain becomes excessively large for determination of radiation at distances even relatively close to the source. We propose combining FDTD with a spatial transformation technique, the Kirchhoff surface integral, for determination of near and far field radiation from microwave or ultra-fast electronic systems. This technique is shown to be extremely accurate, and is often computationally more expedient than use of the FDTD alone.

The present work begins with a description of the Kirchhoff surface integral, including a discussion on implementation. The method is validated by simulation of simple radiating systems in homogeneous space for which exact solutions are available. Next, inhomogeneous material parameters are introduced, and their effects on the radiative fields is demonstrated. Finally, results are presented utilizing this technique in the characterization of radiation from a wideband sub-picosecond system. Simulation results show a significantly more accurate portrait of the far field radiation, compared to the standard model for the far field based on the derivative of the source current in which material parameters are not included.

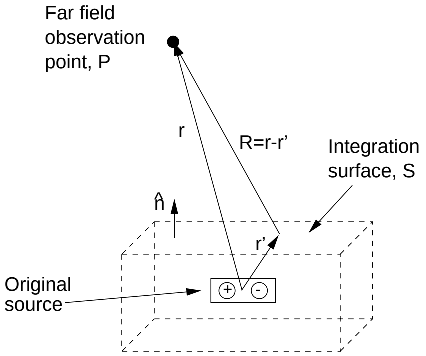

Fig. 1. Typical system in which the Kirchhoff surface integral formulation is utilized. The original source is replaced by the integration surface for calculation of the field at observation point, P.

The Kirchhoff Surface Integral

The Kirchhoff surface integral [3], [4] is one of several near-to-near and near-to-far field transformation techniques [5], [6]. These spatial/temporal transformation techniques are based on Huygens' principle, which states that each point on an expanding wavefront may act as a new source of radiation. These techniques allow determination of the fields anywhere in a homogeneous, source-free problem space in terms of known field values on a surface surrounding a calculation volume (see Figure 1). The Kirchhoff transformation technique differs from the others mentioned above because it is a *scalar* technique, that is, one scalar field quantity is utilized and determined separately in each calcula-

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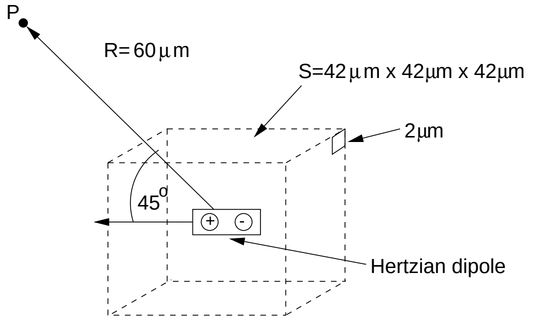


Fig. 2. Structure used to validate the numerical method.

tion. For example, E_z at a far field point is determined only in terms of E_z on the calculation surface.

The Kirchhoff surface integral is given as follows:

Let $\phi(x,y,z,t)$ be a solution of the wave equation with no singularities outside a closed surface S. Let P be a point outside S. Then,

$$\phi(P,t) = \frac{1}{4\pi}\iint_{S'}\left\{[\phi]\frac{\partial}{\partial n'}\left(\frac{1}{R}\right) - \frac{1}{cR}\frac{\partial R}{\partial n'}\left[\frac{\partial\phi}{\partial t}\right] - \frac{1}{R}\left[\frac{\partial\phi}{\partial n'}\right]\right\} ds', \tag{1}$$

where the prime refers to points on the integration surface. Refer to Figure 1 for definition of the remaining terms. The square brackets indicate retarded time corresponding to the time needed for a signal to travel from a point on the surface to P with speed $c = 1/\sqrt{\mu_0\epsilon_0}$.

As stated in [7], the Kirchhoff surface integral is easily implemented using the geometry and discretization of a Yee cell based [1] FDTD code. The Kirchhoff integral requires a similar level of discretization for accurate results. Using difference equations in time and space, each of the terms in (1) may be calculated from quantities already computed in the FDTD code.

Integration is implemented as a “time weighted” summation over the surface S. The delay time between each surface element and the observation point is precalculated. This delay time is used to assign the evolving surface field terms to the proper elements of the observation point field component vector at each time step.

Validation of the Numerical Technique

As a demonstration of the accuracy and efficiency of the Kirchhoff surface integral, let the source of radiation be an ideal Hertzian dipole excited by a Gaussian current pulse, and let $\phi = E_z$. The exact solution is given in many references, for example [8], and will not be repeated here.

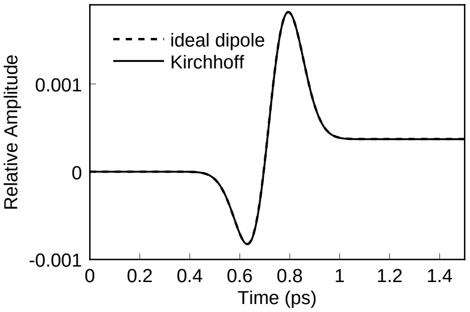


Fig. 3. Comparison of E_z at the observation point calculated with Kirchhoff transformation (solid) and using an ideal dipole (dashed). The observation point is in the near field rather than the far field to demonstrate the accuracy of the method even in this difficult location.

The Gaussian pulse has a pulsewidth of $\tau{=}\beta\Delta t$, and is delayed by $t_0{=}4\tau$. With $\beta{=}32$ and $\Delta x{=}\Delta y{=}\Delta z{=}\Delta{=}2\mu\text{m}$, $\Delta t{=}3.47\text{fs}$, which is 0.9 times the Courant stability condition.

Using the combined FDTD and Kirchhoff integral technique, the z component of the electric field is found at an observation point 45 degrees off the axis of a z-oriented Hertzian dipole source, in line with one corner of the integration surface. See Figure 2. The source is implemented in FDTD using the technique described in [9], *i.e.*, the current distribution is assumed constant over the volume of one FDTD grid cell. Figure 3 indicates this is a reasonable approximation and shows excellent agreement between the exact solution and the solution provided by the numerical technique. The observation point in this example is in the near field rather than the far field to demonstrate the accuracy of the method. Simulations for observation points located at other distances from the surface show a similar level of accuracy.

Inclusion of Inhomogeneous Material Parameters

In the previous section, calculations were performed in a homogeneous problem space. The extent to which inhomogeneous material parameters significantly alter results depends on several factors, including the temporal characteristics of the excitation relative to the dimensions of the structure, and the excitation model used. The effects of these parameters on the simulation are illustrated with a representative structure, again excited by a Gaussian current pulse.

The structure consists of a substrate of GaAs material, with relative permittivity of approximately 12 at the highest frequency involved in the experiment. A worst case scenario is presented, with absorption equal

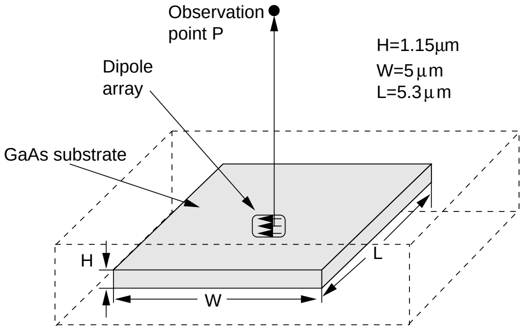


Fig. 4. Structure used to determine the effects of including inhomogeneous material parameters in the simulation.

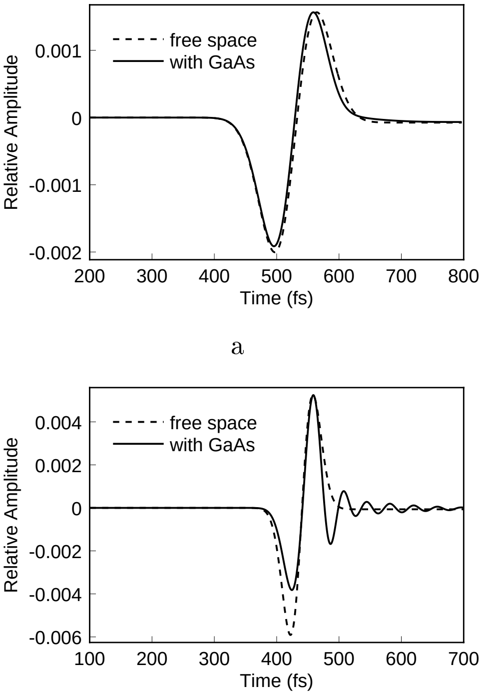
to zero. The dimensions of the structure are shown in Figure 4. For some applications, such as the photoconducting system presented in the next section, a uniformly distributed excitation is assumed in the GaAs substrate. Therefore, the excitation model for this experiment consists of a vertical array of dipoles embedded uniformly in the GaAs substrate, as shown in Figures 4 and 6.

The reflections occurring at the air/GaAs interfaces become significant when the pulse width, τ, is comparable to the transit time through the material. Results are presented in Figure 5 for two cases with pulse widths corresponding to approximately 4 and 2 times the transit time. The observation point is 100μm from the center of the GaAs substrate, where the received pulse is approaching the far field response, *i.e.* the derivative of the excitation. Also shown are the cases for an ideal Hertzian dipole in free space with an appropriate time delay to account for the presence of the GaAs.

It may be seen that for the narrower pulse width, reflections off the GaAs/air interfaces cause ringing. In the extreme case of a narrow pulse excitation relative to the transit time through the GaAs slab, the reflections may make accurate resolution of the received pulse difficult.

Application of the Method to a Photoconducting Structure

The combined FDTD/Kirchhoff surface integral technique is well-suited to the analysis of radiation from a photoconducting structure such as the one shown in Figure 6. In this structure, a sub-picosecond laser pulse is incident on a GaAs substrate, creating electron-hole pairs. Acceleration of the e-h pairs in opposite directions due to the applied bias voltage on the electrodes results in a time-varying dipole source oriented parallel to the substrate surface, and transverse to the biased electrodes. These structures are used in electro-optic sampling applications and in photoconducting switches. The resulting time-varying current density has been modeled using a combined Monte Carlo/FDTD simulation technique reported in previous work [10]. Three typical current pulses are shown in Figure 7 demonstrating the effects of varying the bias voltage and the thickness of the GaAs substrate.



a

b

Fig. 5. Electric field 100μm from the source for two different pulse widths: a) τ=56fs and b) τ=30fs. Transit time through the GaAs substrate is 13.3fs. Dashed lines represent the calculation for an ideal dipole in free space, with an appropriate time delay to account for the presence of the GaAs.

These realistic current pulses contain high frequency content in the form of noise. To study effects caused by the inhomogeneous material parameters, rather than by errors in FDTD modeling, the frequency content of each pulse was limited such that FDTD dispersion was not significant. This was verified by taking the time derivative of the current pulse and comparing to the far field radiation generated by the combined FDTD/Kirchhoff integral method.

Next, the GaAs substrate was added to the simulation. The current pulse shown by the solid curve of Figure 7 was used as excitation of the dipole array shown in Figure 6. The dimensions of the structure are the same as those given in the last example (see

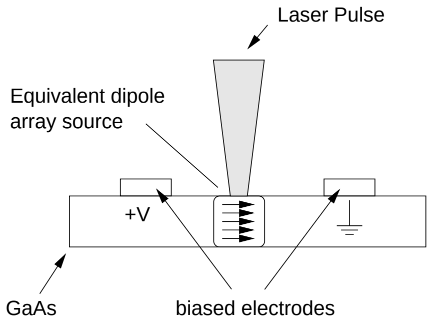


Fig. 6. Typical structure for an electrooptic sampling experiment.

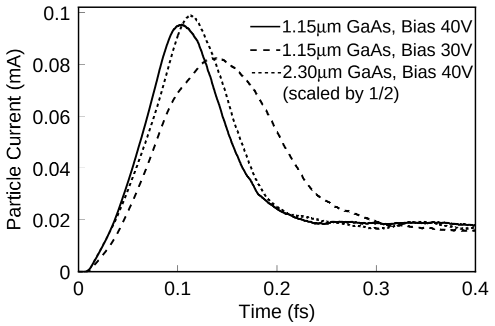


Fig. 7. Comparison three different pulses generated by the photoconducting experiment.

Figure 4). Figure 8 shows that the higher frequency components of the pulse are reflected by the GaAs/air interfaces, distorting the received waveform. These effects would be neglected in a simple derivative model for the far field radiation.

Conclusion

We have demonstrated a computational technique which may be used to accurately and efficiently determine near and far field radiation from microwave and ultra-fast electronic devices. The technique combines the FDTD method and the Kirchhoff surface integral in a spatial and temporal transformation. Implementation was discussed, and the method was validated by comparison to the exact solution for the fields arising from a Hertzian dipole.

The effects of inclusion of materials in simulations of high frequency systems was explored with an example in which a dipole source embedded in a GaAs substrate was excited with current pulses of various durations. These effects were shown to be significant in an application of the method to a photoconducting structure.

The Kirchhoff transformation technique enables more accurate modeling and characterization of the radiation from microwave and millimeter or submillimeter wave structures. The technique described here is, in many situations, more efficient than the FDTD method alone since the wave needs to propagate only to the integration surface where it is transformed in shape and time to the observation point. It is expected that the technique will be of benefit in a wide range of applications.

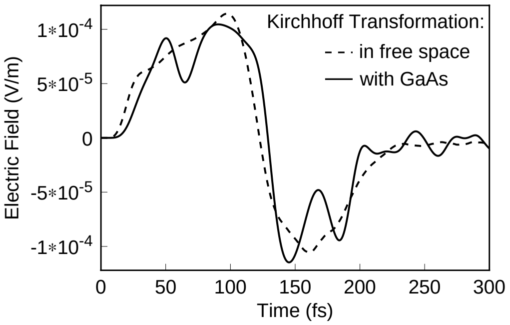


Fig. 8. Comparison of simulation results in free space (dashed line) and with the inclusion of material parameters (solid line).

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