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SHORT VERSION OF DOCTORAL THESIS
ZKRÁCENÁ VERZE DOKTORSKÉ PRÁCE

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ABSTRACT

Simple two-dimensional antenna radiators that serve as building blocks of antenna arrays are analyzed analytically in the time-domain. As a main tool for the analysis the Cagniard-DeHoop method is employed. It is shown that the chosen approach is capable of providing the exact and closed-form time-domain expressions that clearly demonstrate the influence of input parameters involved and elucidate physical insights into the pulsed electromagnetic field radiation behavior. Given numerical examples illustrate important features of the pulsed electromagnetic fields in diverse problem configurations. The obtained results are useful for the efficient design of antenna arrays excited by pulsed fields.

KEYWORDS

time-domain, pulsed electromagnetic field, slot antenna, antenna array, Cagniard-DeHoop technique

ABSTRAKT

Jednoduché dvojrozměrné anténní zářiče, které slouží jako stavební bloky anténních polí, jsou analyticky analyzovány v časové oblasti. Jako hlavní nástroj pro analýzu je použita Cagniard-DeHoopova metoda. Je ukázáno, že zvolený přístup umožňuje získat přesné vzorce v časové oblasti v uzavřeném tvaru, které jasně demonstrují vliv vstupních parametrů a objasňují fyzikální podstatu pulsního elektromagnetického vyzařování. Dané numerické výsledky ilustrují důležité aspekty pulsního elektromagnetického záření v rozličných konfiguracích problémů. Získané výsledky jsou užitečné pro efektivní návrh anténních polí, které jsou buzeny pulsními signály.

KLÍČOVÁ SLOVA

časová oblast, pulsní elektromagnetické pole, štěrbinová anténa, anténní pole, Cagniard-DeHoopova technika

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DECLARATION

I declare that I have elaborated my doctoral thesis on the theme of "Pulsed electromagnetic field radiation from slot antennas" independently, under the supervision of the doctoral thesis supervisors and with the use of technical literature and other sources of information which are all quoted in the thesis and detailed in the list of literature at the end of the thesis.

As the author of the doctoral thesis I furthermore declare that, concerning the creation of this doctoral thesis, I have not infringed any copyright. In particular, I have not unlawfully encroached on anyone's personal copyright and I am fully aware of the consequences in the case of breaking Regulation § 11 and the following of the Copyright Act No 121/2000 Vol., including the possible consequences of criminal law resulted from Regulation § 152 of Criminal Act No 140/1961 Vol.

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(author's signature)

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Chapter 1

Introduction

Recently, with the advent of communication systems based on the transfer, identification and subsequent interpretation of digital signals, there is a growing importance of the time-domain analysis of such systems. One of the actual requirements imposed on modern communication systems is the capability of providing a bundle of services for a high number of customers. These new capabilities bear high demands on the signal processing and front-end parts of communication systems. Since the signals between the transmitting and receiving parts of such communication systems must be steered in specified directions, a utilization of antenna structures that provide a spatial filtering is necessary. This calls for the use of antenna arrays and the investigation of their pulsed field radiation behavior.

The important building block of an antenna array is the radiator itself which can take various forms. One of the practically well verified antenna array elements consists of an aperture that can be realized as an open end of a waveguide or as a horn. Since the aperture type antennas are frequently used in intricate ambient conditions (for example, in aeronautical applications), their openings are usually protected by a dielectric covering that can significantly affect the radiation behavior. A synthesis of antenna arrays is therefore unavoidably connected with an understanding of the antenna element behavior itself in diverse circumstances.

Beside of this, a pulsed field behavior of simple aperture radiators and antenna arrays is of a great interest in the design and optimisation of inter- and intra-chip wireless pulsed signal transfer channels in integrated circuits. The need of wireless integrated circuit interconnects that are capable of transfering pulsed-shaped (bit-like) signals originates in the trend of miniaturization of electronic circuit components and in the using of still higher bit rates, which leads to the impossibility of realising the required interconnects in the classical electrical conductive-wire manner. The research on this subject is nowadays in full progress [20, 21].

1.1 Compendium of relevant approaches

In order to satisfy the high demands of advanced communication systems, an efficient design of antenna array requires a tool that clearly demonstrates the influence of the involved configurational and excitation parameters. This requirement can hardly be met with traditional numerical approaches (Finite Difference Method, Finite Element Method,

Method of Moments) that provide single-purpose results giving superficial insights only. On this account, an application and investigation of analytical techniques is in our scope of interest. Although antenna enginnering has a long history, the pulsed field behavior of antenna systems is still a subject seldom touched upon. In this respect, the analysis of pulsed behavior of antenna systems and the time-domain description of an antenna itself has received attention in [13, 3, 30].

The early works on the analysis of microwave components with a construction based on the horizontally stratified media lean upon the formulation of Sommerfeld [31, 32]. Sommerfeld's approach involves the Fourier transformation with respect to time followed by the 'cylindrical' form of the two-dimensional Fourier transformation with respect to the spatial coordinates parallel to the media interface (Fourier-Bessel transformation). The same theoretical machinery led to the development of the frequency-domain integral equation technique [26]. The main drawback of this approach is a demanding numerical solution of an inverse spatial-transformation integral (commonly known as Sommerfeld's integral). In general, the Sommerfeld-type integral has an unbounded domain of integration, oscillatory integrands containing the pole and branch-point singularities. The mentioned difficulties are ussually solved via the proper choice of an integration contour and by special extrapolation techniques accelerating the convergence of numerical integration [25]. Despite of the inherent drawbacks, the frequency-domain integral equation technique has proved to be useful for analyses of various microwave devices based on the microstrip structure [27].

Regarding the radiation from flanged parallel-plate waveguides excited by an incident mode a number of approaches have been formerly applied. They are mainly focused on an aperture radiator description in terms of the aperture admitance and self-reflection coefficients connected with a particular excitation mode. These approaches are based on a variational problem formulation [24], on the correlation matrix technique [23] or on the asymptotical ray method [22]. The 'classical' approach is described in Harrington's book [18, Sec. 3.11]. In the latter, the one-dimensional Fourier transforms are applied with respect to time and horizontal spatial coordinate. The difficulties arise when one attempts to perform an inverse spatial Fourier transformation. Again, this can be done numerically or, for particular cases, through the asymptotic integration techniques [16, Sec. 4].

The difficulties involved in Sommerfeld's formulation have been avoided by De Hoop's modification of Cagniard's method [4, 5] which is widely known as the Cagniard-DeHoop technique [8, 9, 17, 1, 2, 6]. The Cagniard-DeHoop method is based on the combination of a unilateral Laplace transformation with respect to time with the spatial slowness representation such that the time-domain counterpart is found by inspection, without making use of an inverse Laplace transformation. The corresponding procedure based on the time Fourier transform can be found in Chew's book [7, Sec. 4.2]. The Cagniard-DeHoop allows for the inclusion of Boltzmann-type relaxation behavior (which includes, for example, Lorentz-line and Drude/Debye-absorption behavior) at the expense of having to use more complicated theorems of the time Laplace transformation. In this respect, the generalized Cagniard-DeHoop technique [12, 10, 14] employing the Schouten-VanDerPol theorem [35, 29] has been developed.

1.2 Statement of the problem

Based on the observation that all other known approaches (which include both numerical and analytical ones) do not yield exact solutions of the problem in hand, the pulsed field radiation behavior of the slot antennas is investigated by means of the Cagniard-DeHoop technique. The Cagniard-DeHoop method yields the closed-form expressions providing the pulsed radiated electromagnetic fields as functions of position and time. Such expressions clearly demonstrate the influence of the parameters involved and thus provide useful insights into the slot antenna synthesis. They serve as the basis for carrying out parameter sensitivity analyses as to pulse shapes in relation to the geometrical and physical parameters of the configuration. Since the expressions obtained can be evaluated at a given observation position and within any finite time window with any prescribed accuracy, they can serve as a benchmark tool in the use of purely computational techniques that are required for the configurations of higher complexity.

Our investigation is aimed at two-dimensional structures only. More precisely, the pulsed electromagnetic field radiation from a slot, that would be conceived as an open end of the parallel-plate waveguide, is thoroughly investigated in a number of configurations. An excitation field distribution over the radiating aperture is prescribed in two ways. The uniform excitation field distribution corresponds to the radiation from a parallel-plate waveguide carrying the Transverse ElectroMagnetic (TEM) mode, while a nonuniform excitation field distribution corresponds to, in our case, the Transverse Magnetic (TM) modal excitation. The applied theory can be further generalized to account for three-dimensional radiators.

1.3 Outline of the thesis

The analysis of the slot antennas effectuated throughout this thesis is based on the Maxwell's laws of macroscopic electromagnetic theory [19]. The electromagnetic field equations as applied throughout the thesis are briefly discussed in Chapter 2. The comprehensive survey of the subject can be found in [11, Part 3].

The main part of the thesis consists of seven chapters dealing with problems of increasing complexity. In view of consistency, each of these parts is treated at full length and can be regarded, to a certain extent, as a separate, self-contained account. Throughout the thesis we investigate the pulsed-field radiation behavior of a slot in an electrically perfectly conducting screen. The source exciting the structures is modeled as a prescribed distribution of the transverse electric field across the radiating slot.

Starting with a freestanding infinitesimal slot (line source) we gradually extend the problem complexity by inclusion an additional electrically conducting screen or a dielectric covering layer. Subsequently, we proceed to the more realistic radiator by considering a finite width of the slot. Again, the pulsed radiation from this slot is investigated in the presence of an electrically conducting screen or a dielectric layer. Finally, it is demonstrated how to deal with the spatially nonuniform distribution of the excitation, as occurs in the case of the modal excitation. For the sake of briefness, most of the chapters are suplemented by an Appendix, where the generic integral representation applying to the corresponding problem is solved. A number of numerical results that illustrate important features of corresponding wave phenomena are given.

Chapter 3 addresses the radiation properties of a slot of infinitesimal width in a two-dimensional configuration. The solution of the latter problem is solvable also in the frequency domain and can be found in the literature (see, for example [16]). In this part, the radiated pulsed fields are found via the Cagniard-DeHoop technique and also with the help of the corresponding scalar Green's function.

Chapter 4 can be considered as a generalization of the previous chapter and as a preparatory step for the next one. Here, the pulsed radiation from a narrow slot is investigated in the presence of a perfectly conducting screen that is placed above the slot. This chapter brings new features as the reflected wave constituents that occur on account of the additional screen.

Throughout Chapter 5, our considerations are aimed at the narrow slot antenna configuration covered by a dielectric slab. Thanks to the presence of the dielectric covering, the pertaining wave motion appears as the superposition of a number of propagating, reflecting, and refracting wave constituents. The exact solution of this problem can be found in [34] where the attention was focused on the evaluation of the field pulse shapes at dielectric/air interface. This has been extended here such that the closed-form expressions for radiated fields are given in the dielectric layer, at the dielectric/vacuum interface as well as in the vacuum half-space.

In the next chapters, the problem has been generalized by considering a finite slot width. A pulsed field radiation from a freestanding wide slot is investigated in Chapter 6. Here it is shown that the excitation via a wide slot shows additional features in that the corners of the waveguide feed show a separate diffractive behavior with accompanying wavefronts. The results of this chapter have been used for the description of pulsed radiation from a simple antenna array configuration [33].

Again, Chapter 7 can be considered as a certain generalization of the previous chapter and as a preparatory step for the next one. Here, the wide slot from Chapter 6 is analyzed in the presence of a perfectly conducting screen. It is shown that this additional screen causes reflections of diffractive and plane radiated wave fields.

Chapter 8 deals with the pulsed electromagnetic radiation from a wide slot that is covered by a dielectric layer [15]. On account of the presence of the dielectric slab, the pertaining wave motion appears as the superposition of a number of propagating, reflecting, and refracting wave constituents emanating from the corners of the feeding waveguide in addition to the plane wave propagating and reflecting above the radiating slot.

Finally, in Chapter 9 the problem of a nonuniform spatial distribution of an excitation field (as in the case of a modal excitation in the radiating aperture) is addressed. It is shown that the modal aperture excitation can be taken into account at the expense of having to evaluate an additional one-dimensional integral over a finite time-window.

In conclusion, the accomplishments of the thesis and the prospective aims are summarized.

In this short version of the thesis, only the pulsed electromagnetic field radiation from a coated wide slot is briefly illustrated. The comprehensive theory in this respect is given in Chapter 8 and Appendix B of the thesis.

Chapter 2

The electromagnetic field equations

Summary

In this chapter, the electromagnetic source-free field equations, as used throughout the thesis, are given. Since all problem configurations, as well as their excitation, are independent of one of the spatial coordinates, our starting equations take on a particular form that is derived here.

2.1 The basic equations

Throughout the thesis, the pulsed electromagnetic radiation from a two-dimensional slot antenna is evaluated (see Fig. 2.1). It is assumed that a radiating aperture $\mathcal{A} = \{-w/2 < x_1 < w/2, -\infty < x_2 < \infty, x_3 = 0\}$ of a width w (w is vanishing for a narrow slot antenna, w is finite for a wide slot antenna) is mounted on a perfectly electrically conducting screen $\mathcal{S} = \{(-\infty < x_1 < -w/2) \cup (w/2 < x_1 < \infty), -\infty < x_2 < \infty, x_3 = 0\}$ and radiates into a linear, time invariant, instantaneously and locally reacting, homogeneous and isotropic domain $\mathcal{D}$ described by its scalar electric permitivity ϵ and scalar magnetic permeability μ.

In this domain, the nonzero electromagnetic wave field quantities satisfy the electromagnetic field equations [11, Sec. 18.3]

$$-\boldsymbol{e}_{k,m,p}\partial_m H_p + \epsilon\partial_t E_k = 0 \tag{2.1}$$

$$\boldsymbol{e}_{j,n,r}\partial_n E_r + \mu\partial_t H_j = 0 \tag{2.2}$$

where $\boldsymbol{e}_{k,m,p}$ is the Levi-Civita tensor and

$$\begin{aligned} E_k &= E_k(\boldsymbol{x}, t) \quad \text{is the electric field strength [V/m]}, \\ H_p &= H_p(\boldsymbol{x}, t) \quad \text{is the magnetic field strength [A/m]}. \end{aligned}$$

The excited field quantities are causally related to the x_2-independent excitation E_1 field distribution on the radiating aperture

$$\lim_{x_3 \downarrow 0} E_1(x_1, x_3, t) = [V_0(t)/w]\Omega(x_1)\Pi(x_1/w) \tag{2.3}$$

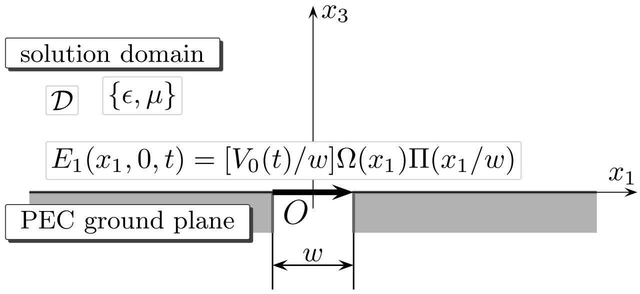


Figure 2.1: Generic configuration with indication of the aperture feeding.

for $t > 0$, $x_1 \in \mathbb{R}$. Here, $V_0(t)$ is a feeding pulse, $\Omega(x_1)$ describes a spatial distribution of an excitation field and $\Pi(x)$ is the rectangular function defined with the help of the Heaviside step function $H(x)$ as

$$\Pi(x) = H(x + 1/2) - H(x - 1/2) \tag{2.4}$$

On account of the problem configuration that is x_2-independent, the electromagnetic field equations can be written out in terms of their components as

$$\partial_3 H_2 + \epsilon \partial_t E_1 = 0 \tag{2.5}$$
$$-\partial_1 H_2 + \epsilon \partial_t E_3 = 0 \tag{2.6}$$
$$-\partial_1 E_3 + \partial_3 E_1 + \mu \partial_t H_2 = 0 \tag{2.7}$$

and

$$-\partial_3 E_2 + \mu \partial_t H_1 = 0 \tag{2.8}$$
$$\partial_1 E_2 + \mu \partial_t H_3 = 0 \tag{2.9}$$
$$\partial_1 H_3 - \partial_3 H_1 + \epsilon \partial_t H_2 = 0 \tag{2.10}$$

The Eqs. (2.5) – (2.7) interrelate $\{E_1, E_3, H_2\}(x_1, x_3, t)$ components (Transverse Magnetic, or TM, with respect to x_3) while the Eqs. (2.8) – (2.10) interrelate $\{H_1, H_3, E_2\}(x_1, x_3, t)$ components (Transverse Electric, or TE, with respect to x_3). Since the excitation is included in via the excitation condition (2.3) for pulsed E_1 field component, only the TM field components are nonzero.

Chapter 3

Pulsed electromagnetic field radiation from a wide slot antenna with a dielectric layer

Summary

The pulsed electromagnetic field radiated from a 2D slot antenna of a finite width covered by a dielectric layer is analytically investigated via the application of the Cagniard-DeHoop technique. Upon describing the problem configuration we provide a number of numerical examples. The corresponding theory can be found in Chapter 8 and Appendix B of the thesis.

3.1 Introduction

With the rapid development of communication systems whose operation is based upon the transfer of pulsed electromagnetic fields and the detection and subsequent interpretation of the pertaining digital signals, there is a need for the mathematical analysis of model configurations where the influence of (a number of) the system parameters on the performance shows up in closed-form analytic expressions that characterize the physical behavior. Parameters in this respect are: the pulse shape of the excitation (characterized by the pulse rise time and the pulse time width of a unipolar pulse), the thickness and the dielectric properties of the slab, the width of the slot, as well as the position of observation relative to the exciting slot. The present chapter aims at providing such a tool with regard to the pulsed radiation behavior of a wide slot antenna covered with a dielectric layer in a two-dimensional setting.

More precisely, we consider a slot in a perfectly electrically conducting planar screen with a uniform finite width. Across the slot a prescribed distribution of the transverse electric field is applied. The pulse shape of the exciting field is arbitrary. In front of the slotted plane there is a homogeneous, isotropic dielectric slab of uniform thickness. The structure further radiates into free space.

Upon application of the Cagniard-DeHoop technique, the closed-form and exact expressions describing the radiated pulsed fields as functions of position and time are obtained [15]. It is shown that the excitation via a wide slot shows additional features in that the corners of the waveguide feed show a separate diffractive behavior with accompanying wavefronts. In this case, the wave motion radiated from such slot consists of two sets of upgoing and downgoing cylindrical waves emanating from the edges of the slot in addition to the plane waves propagating and reflecting above the wide slot.

The obtained expressions can serve a purpose of benchmarking the performance of purely computational techniques that have to called upon in the more complicated configurations met in practice, in particular the ones in patch antenna design, where the field in the present chapter represents the field 'incident' on the geometry of the patches located on the dielectric/free-space interface.

The last section provides a number of illustrative numerical examples for a variety of parameters, all chosen such that the pulse time width is smaller than the travel time needed to traverse the slab and such that the separate arrivals from the two edges can be distinguished. This section is divided into two subsections. At first, numerical examples that illustrate the distortion of pulse shapes (of continuous components across the interface) at the vacuum/dielectric interface due to the presence of a dielectric layer are given. The next subsection shows the time-evolution of the Poynting vector in the dielectric layer, dielectric/vacuum interface and in vacuum is given. This example is further supplemented with the illustration of Cagniard-DeHoop paths connected with the observation point in the vacuum half-space for the first two wave constituents.

3.2 Description of the configuration and formulation of the field problem

The configuration examined is shown in Fig. 3.1. The configuration consists of an unbounded electrically perfectly conducting screen $\mathcal{S} = \{(-\infty < x_1 < -w/2) \cup (w/2 < x_1 < \infty), -\infty < x_2 < \infty, x_3 = 0\}$ with a feeding aperture $\mathcal{A} = \{-w/2 < x_1 < w/2, -\infty < x_2 < \infty, x_3 = 0\}$ of the finite width $w > 0$. The covering dielectric slab occupies the domain $\mathcal{D}_1 = \{-\infty < x_1 < \infty, -\infty < x_2 < \infty, 0 < x_3 < d\}$. The structure radiates into the vacuum half-space $\mathcal{D}_0 = \{-\infty < x_1 < \infty, -\infty < x_2 < \infty, d < x_3 < \infty\}$. The spatial distribution of electric permittivity and magnetic permeability is

$$\{\epsilon, \mu\} = \begin{cases} \{\epsilon_0, \mu_0\} & \text{in } \mathcal{D}_0 \\ \{\epsilon_1, \mu_1\} & \text{in } \mathcal{D}_1 \end{cases} \tag{3.1}$$

The corresponding electromagnetic wave speeds and characteristic admitances are $c_0 = (\epsilon_0\mu_0)^{-1/2}$, $c_1 = (\epsilon_1\mu_1)^{-1/2}$ and $\eta_0 = (\epsilon_0/\mu_0)^{1/2}$, $\eta_1 = (\epsilon_1/\mu_1)^{1/2}$, respectively. The antenna aperture is fed by the uniformly distributed, x_2-independent, electric field

$$E_1(x_1, 0, t) = V_0(t)/w \quad \text{in } \mathcal{A} \tag{3.2}$$

where $V_0(t)$ is the feeding 'voltage'. Since the excitation, as well as the configuration, are independent of x_2, the non-zero components of the electric field strength $\{E_1, E_3\}(x_1, x_3, t)$

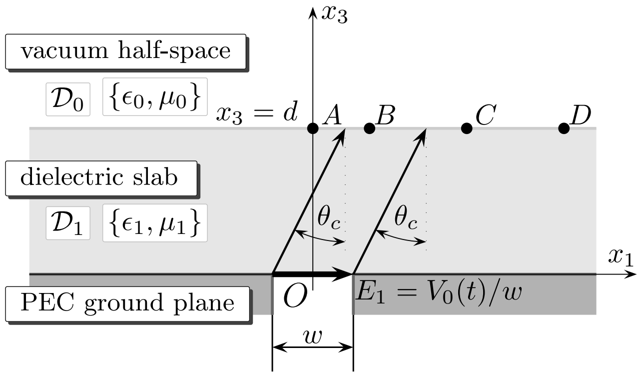


Figure 3.1: Configuration with indication of the critical angle $\theta_c = \arcsin(c_1/c_0)$. Positions of the observation points $\{B, C, D\}$ are not true-to-scale with those chosen in Section 3.3.1.

and the magnetic field strength $H_2(x_1, x_3, t)$ satisfy in $\mathcal{D}_0$ and $\mathcal{D}_1$ the source-free field equations (cf. Eqs. (2.5) – (2.7))

$$\partial_1 H_2 - \epsilon \partial_t E_3 = 0 \tag{3.3}$$

$$\partial_3 H_2 + \epsilon \partial_t E_1 = 0 \tag{3.4}$$

$$\partial_1 E_3 - \partial_3 E_1 - \mu \partial_t H_2 = 0 \tag{3.5}$$

The interface boundary conditions require that

$$\lim_{x_3 \downarrow d} E_1(x_1, x_3, t) = \lim_{x_3 \uparrow d} E_1(x_1, x_3, t) \quad \text{for all } x_1 \text{ and } t \tag{3.6}$$

$$\lim_{x_3 \downarrow d} H_2(x_1, x_3, t) = \lim_{x_3 \uparrow d} H_2(x_1, x_3, t) \quad \text{for all } x_1 \text{ and } t \tag{3.7}$$

while the excitation condition is (cf. Eq. (2.3))

$$\lim_{x_3 \downarrow 0} E_1(x_1, x_3, t) = [V_0(t)/w]\Pi(x_1/w) \quad \text{for all } t \tag{3.8}$$

with $\Pi(x)$ denoting the rectangular function (see Eq. (2.4)). It is assumed that $V_0(t)$ starts to act at $t = 0$ and that prior to this instant the field vanishes throughout the configuration.

Upon solving the system (3.3)–(3.8) we arrive at the closed-form time-domain expressions that are given in the thesis. Numerical examples are presented in the following sections.

3.3 Illustrative numerical examples

This section provides illustrative numerical results for the case of excitation with the power exponential pulse with parameter $\nu = 2$ ($t_w/t_r = 1.8473$), shown in Fig. 3.2. In it, the normalized $V_0(t)$ is $V_0(t)/V_{\max}$ and normalized time is $c_0 t/d$ (see Appendix E of the thesis). This activating pulse is used throughout this section. The properties of the slab are taken as $\{\epsilon_1, \mu_1\} = \{4\epsilon_0, \mu_0\}$.

Table 3.1: Arrival times of time-domain constituents at the vacuum/dielectric interface.

Arrival times								
	A	B	C	D	A	B	C	D
order	Head-wave (left edge)				Body-wave (left edge)			
$[n]$	$c_0T^{[n]}_{\mathrm{HWa}}/d$				$c_0T^{[n]}_{\mathrm{BWa}}/d$			
0	-	3.2321	5.2321	7.2321	2.2361	3.6056	7.2801	11.1803
1	-	-	8.6962	10.6962	6.0828	6.7082	9.2195	12.5300
2	-	-	12.1603	14.1603	10.0499	10.4403	12.2066	14.8661
3	-	-	-	17.6244	14.0357	14.3178	15.6525	17.8045
4	-	-	-	-	18.0278	18.2483	19.3132	-
order	Head-wave (right edge)				Body-wave (right edge)			
$[n]$	$c_0T^{[n]}_{\mathrm{HWb}}/d$				$c_0T^{[n]}_{\mathrm{BWb}}/d$			
0	-	-	4.2321	6.2321	2.2361	2.2361	5.3852	9.2195
1	-	-	7.6962	9.6962	6.0828	6.0828	7.8102	10.8167
2	-	-	-	13.1603	10.0499	10.0499	11.1803	13.4536
3	-	-	-	16.6244	14.0357	14.0357	14.8661	16.6433
4	-	-	-	-	18.0278	18.0278	18.6815	-

The first part of this section shows pulse shapes of $\{E_1, H_2\}(x_1, d, t)$ at the level of vacuum/dielectric interface, while the second subsection gives the time evolution of the Poynting vector within a certain region of space at successive observation times. The last part is supplemented by examples of Cagniard-DeHoop contours associated with the evaluation of pulse shapes in the vacuum.

3.3.1 Examples of pulse shapes at the vacuum/dielectric interface

In any finite time window of observation, only a finite number of time-domain constituents yields a non-zero contribution, while in the range of critical refraction only a subset of these contributions have a head-wave part. The objective of our analysis is to compare the pulse shapes of the different constituents with the ones that the slot antenna would radiate into a half-space with the properties of $\mathcal{D}_0$. The comparison is carried out on the vacuum/dielectric interface.

Four positions of observation at $x_3 = d$ have been selected: (A) $x_1/d = 0$, (B) $x_1/d = 1$, (C) $x_1/d = 3$, (D) $x_1/d = 5$ (indicated, not to scale, in Fig. 3.1). The observation point (A) lies right in front of the radiating slot. The observation point (B) is within the range of critical refraction associated with the left edge of the slot and outside the range of critical refraction associated with the right edge of the slot, while the observation points (C) and (D) are within the range of critical refraction associated with both edges of the slot. The time window of observation is taken as $0 < c_0t/d < 20$. The width of the slot w and the thickness of the dielectric slab d are interrelated as $d/w = 1$. The rise time of the excitation pulse t_r is taken as half of the free-space travel time across the slab. As described in Appendix E of the thesis, the pulse time width t_w is related to the pulse rise time t_r, which gives $c_0t_w/d = 0.9236$ for $\nu = 2$. The arrival times of the different contributions are collected in Table 3.1. Figures 3.3 – 3.6 show the results. In them, the normalized time is c_0t/d, the normalized electric field is $E_1w/V_{\max}$ while the normalized magnetic field is $(\mu_0/\epsilon_0)^{1/2}H_2w/V_{\max}$. The observation point (A) lies outside the range of critical refraction range of both radiating edges. Here, the wave motion consists of a superposition of a plane-wave contribution emanating from the radiating slot and cylindrical waves emanating from the edges of the slot. No head-wave contribution occurs. The observation point (B) lies within the range of critical refraction of the left edge of the slot and outside the one associated with the right edge. Here, the wave motion consists of a superposition of cylindrical waves emanating from both edges of the slot and head-wave contributions emanating form the right edge of the slot. The observation points (C) and (D) lie within the range of critical refraction of both edges of the slot. Here, the wave motion consists of a superposition of cylindrical waves emanating from both edges of the slot and head-wave contributions emanating form both edges of the slot. In all those regions where head-wave contributions occur pulse shapes show up that drastically differ from the excitation.

3.3.2 Time evolution of the Poynting vector

The (color) vector density plots Figs. 3.7 – 3.8 show the time snaps of the two-component Poynting vector

$$S_1 = -E_3H_2 \tag{3.9}$$

$$S_3 = E_1H_2 \tag{3.10}$$

normalized with respect to

$$|\boldsymbol{S}|_{\text{ref}} = (V_{\max}/w)^2(\epsilon_0/\mu_0)^{1/2} \tag{3.11}$$

The reference magnitude $|\boldsymbol{S}|_{\text{ref}}$ corresponds to the maximum value of the Poynting vector as it would be carried by a TEM-mode in a parallel-plate waveguide that would be a feeding of the radiating aperture. The spatial domain of observation is taken as $\{-3 \leq x_1/d \leq 3, 0 \leq x_3/d \leq 3\}$ and two observation times are chosen as $c_0t/d = \{2, 4\}$. The width of the slot w and the thickness of the dielectric slab d are interrelated via $d/w = 1$.

Figure 3.7 shows the time evolution of the Poynting vector for the power-exponential pulse excitation with $c_0t_w/d = 0.9236$. In Fig. 3.7(a) the wavefront just reaches the dielectric/vacuum interface. Because of the relatively high ratio of the spatial extent of the excitation pulse compared with the slot width, the radiation of the slot resembles the one that would be radiated from a line source. In Fig. 3.7(b), the reflected wave constituents as well as head-wave constituent are clearly seen.

In order to illustrate the dependence on the relation between the spatial extent of the excitation pulse and the slot width, the rise time t_r of the excitation pulse has been decreased to one tenth of the free-space travel time across the slab. The corresponding normalized pulse time width is $c_0t_w/d = 0.1847$. For this case, Fig. 3.8 shows the Poynting vector distribution at the two observation times $c_0t/d = 2$ and $c_0t/d = 4$. Overlapping cylindrical waves arising from the radiating edges and a plane-wave contribution emanating from the slot are clearly distinguishable. The electromagnetic power density radiated from the slot is now concentrated within the narrower beam propagating above the radiating slot.

Our analysis can be used to further study the possibilities of adapting the excitation pulse to design requirements associated with optimum signal transfer [28] and/or time-domain beam shaping of antenna arrays.

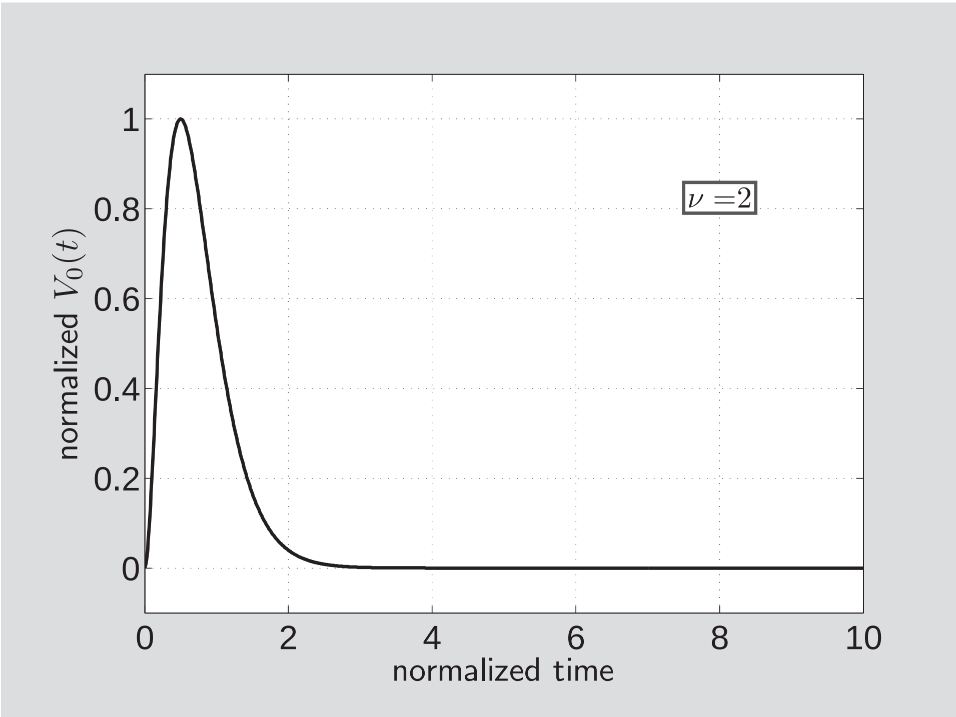


Figure 3.2: The power exponential excitation pulse shape.

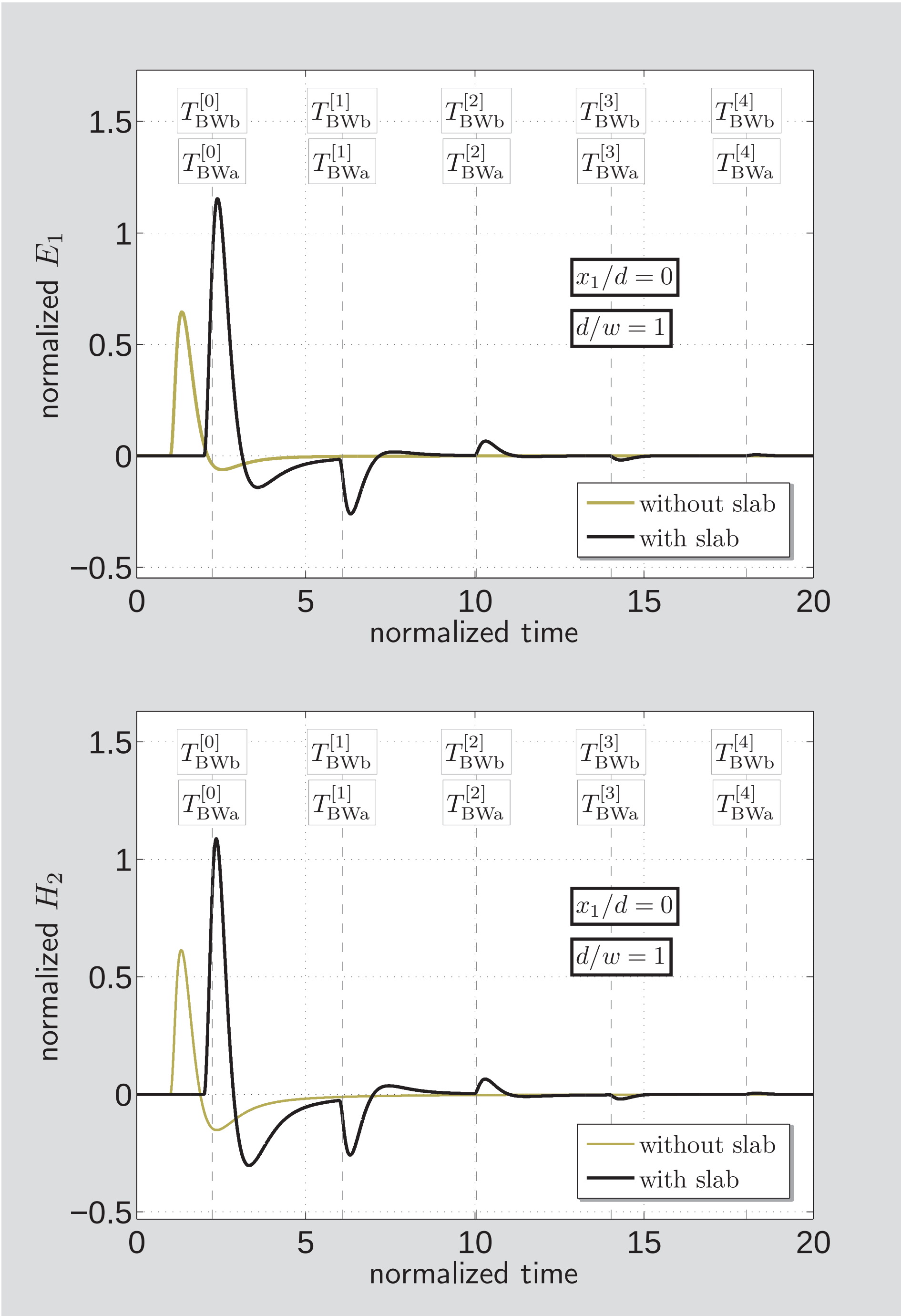


Figure 3.3: Normalized E_1 field time-domain response and normalized H_2 field time-domain response at $x_1/d = 0$.

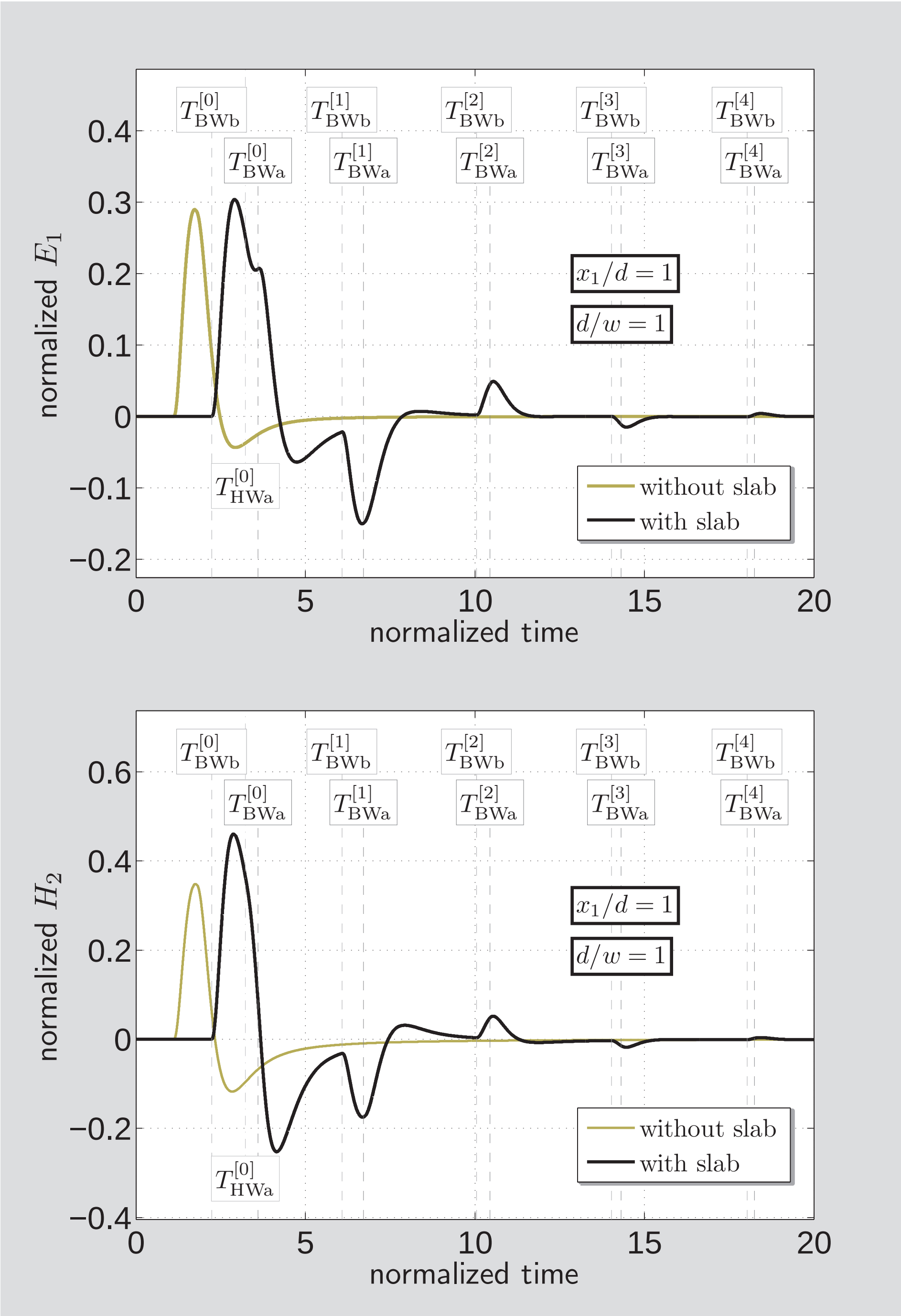


Figure 3.4: Normalized E_1 field time-domain response and normalized H_2 field time-domain response at $x_1/d = 1$.

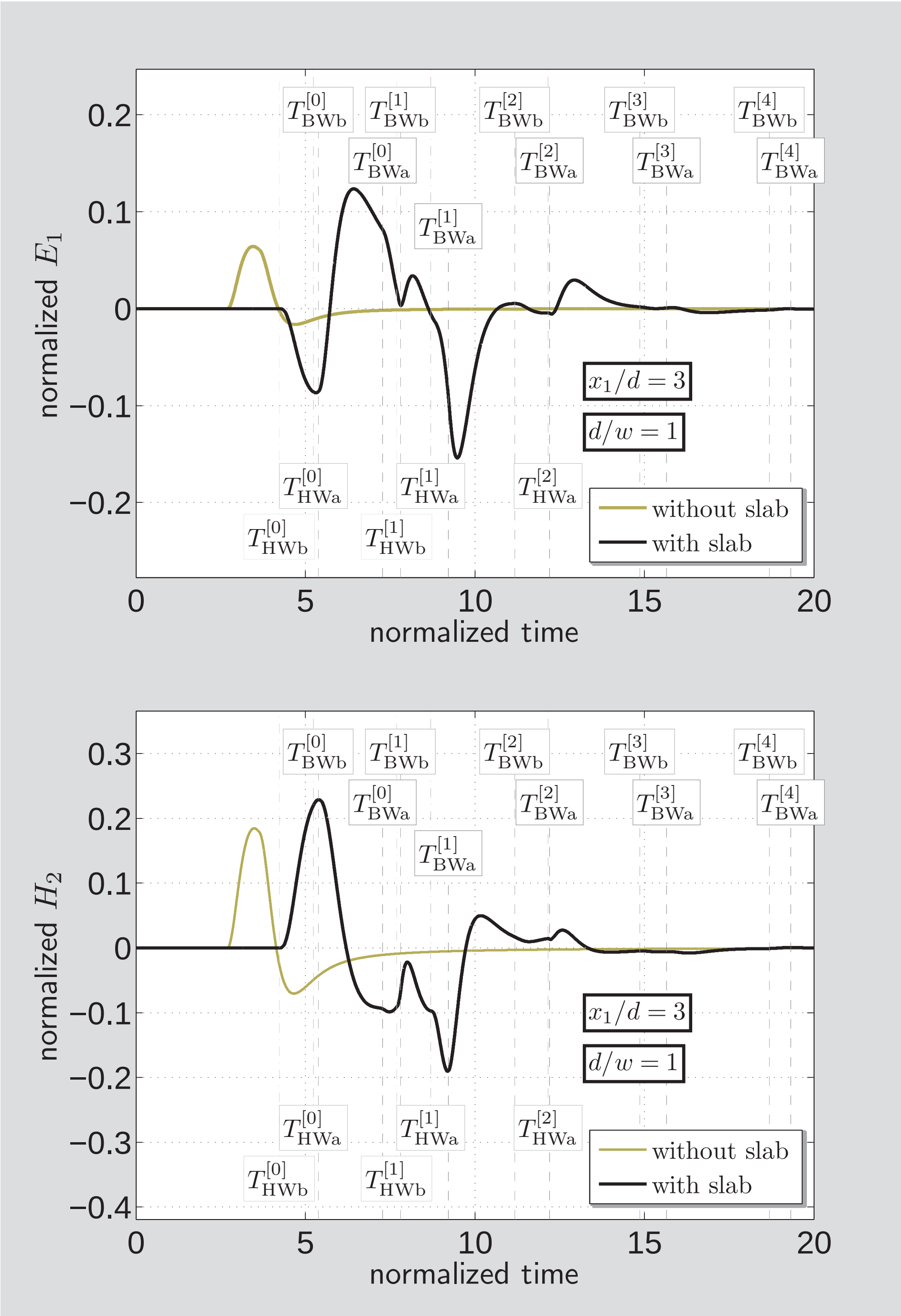


Figure 3.5: Normalized E_1 field time-domain response and normalized H_2 field time-domain response at $x_1/d = 3$.

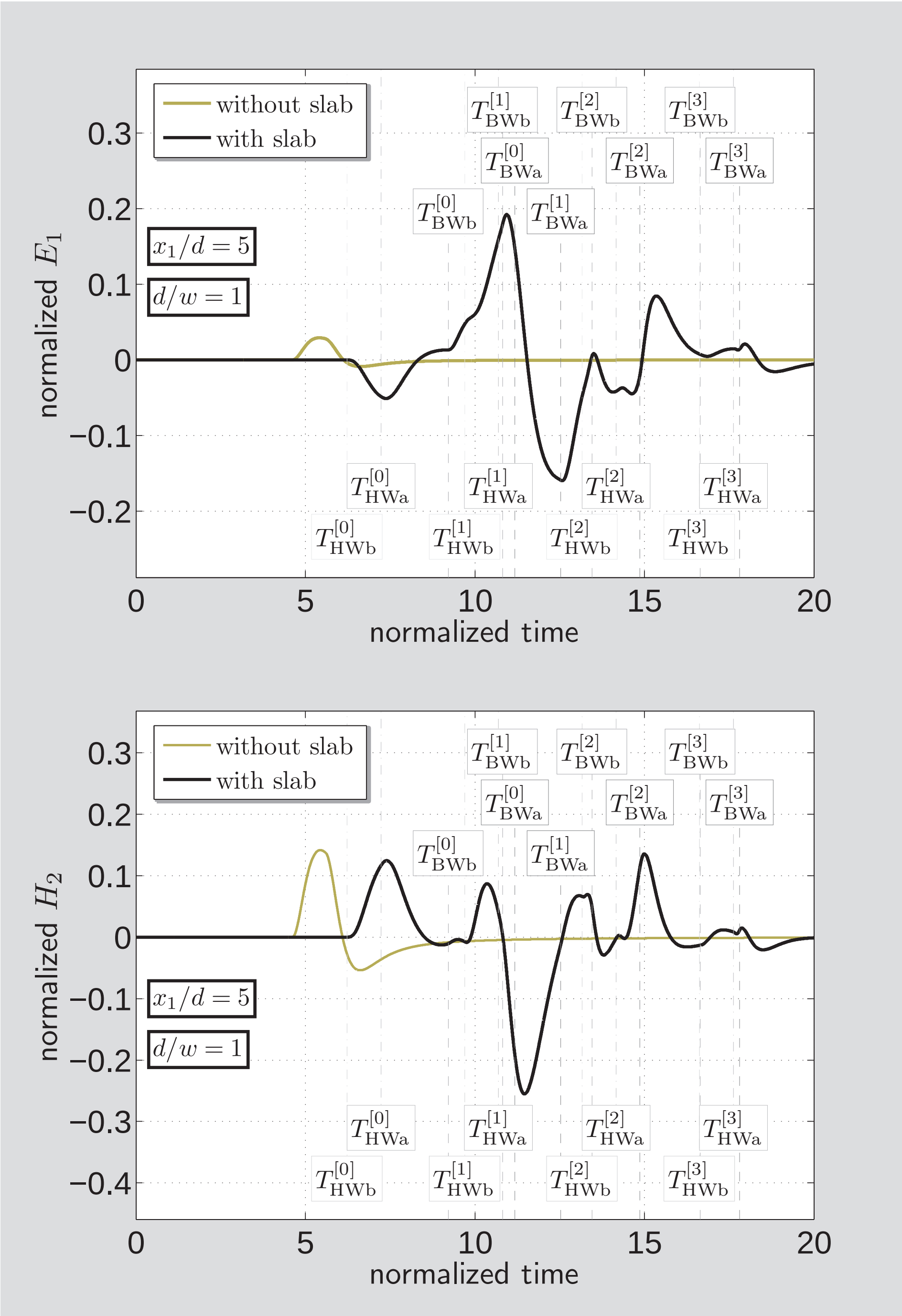
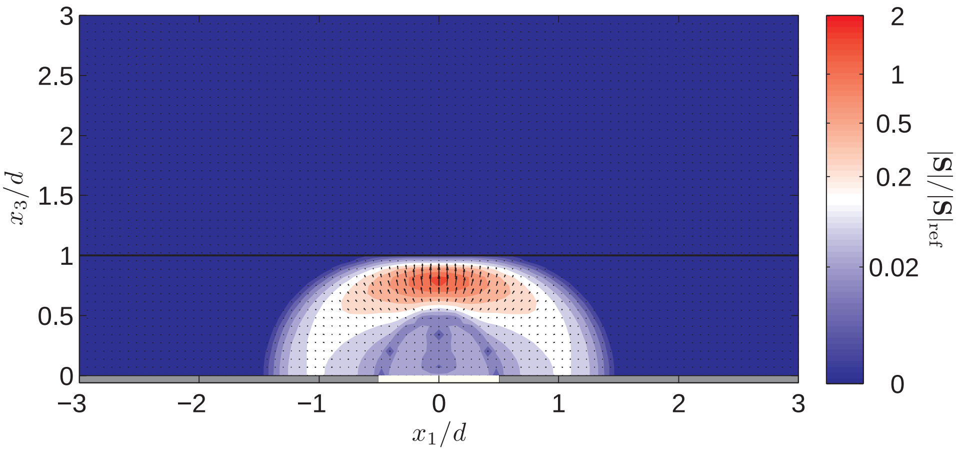
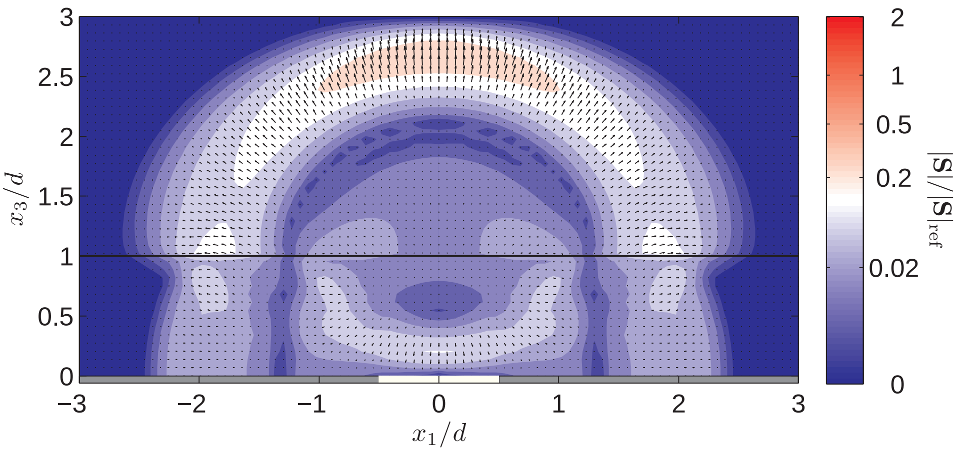


Figure 3.6: Normalized E_1 field time-domain response and normalized H_2 field time-domain response at $x_1/d = 5$.

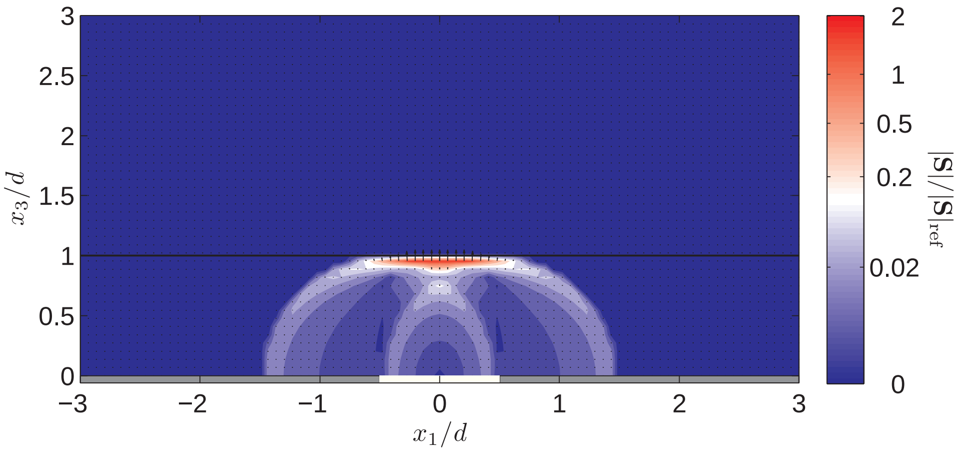


a

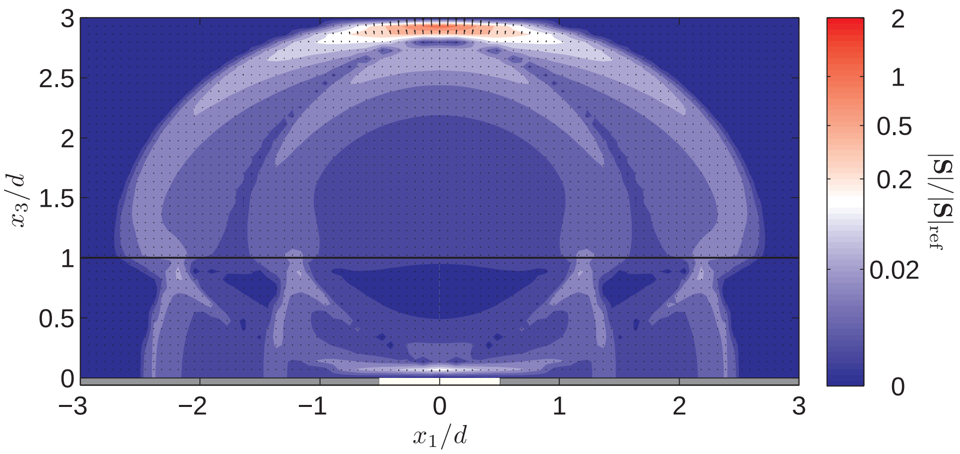


b

Figure 3.7: Normalized Poynting vector of the EM field at (a) $c_0t/d = 2$; (b) $c_0t/d = 4$. Slab thickness versus slot width is $d/w = 1$ and electromagnetic parameters of the dielectric slab are $\{\epsilon_1, \mu_1\} = \{4\epsilon_0, \mu_0\}$. Parameters of the excitation pulse are $c_0t_w/d = 0.9236$, $\nu = 2$.



a



b

Figure 3.8: Normalized Poynting vector of the EM field at (a) $c_0t/d = 2$; (b) $c_0t/d = 4$. Slab thickness versus slot width is $d/w = 1$ and electromagnetic parameters of the dielectric slab are $\{\epsilon_1, \mu_1\} = \{4\epsilon_0, \mu_0\}$. Parameters of the excitation pulse are $c_0t_w/d = 0.1847$, $\nu = 2$.

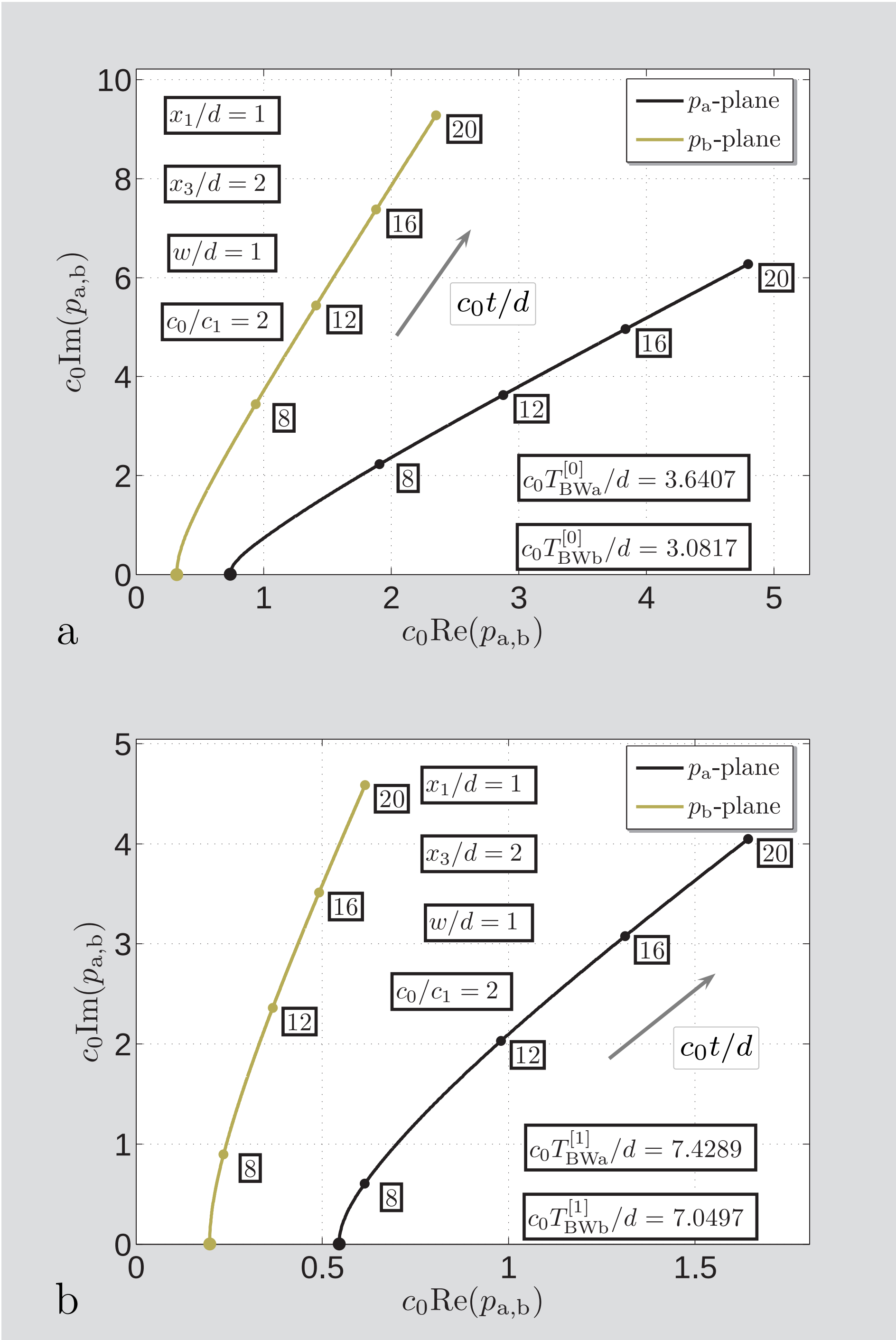


Figure 3.9: Examples of Cagniard-DeHoop contours associated with the first two successive time-domain constituents in vacuum (a) $n = 0$; (b) $n = 1$.

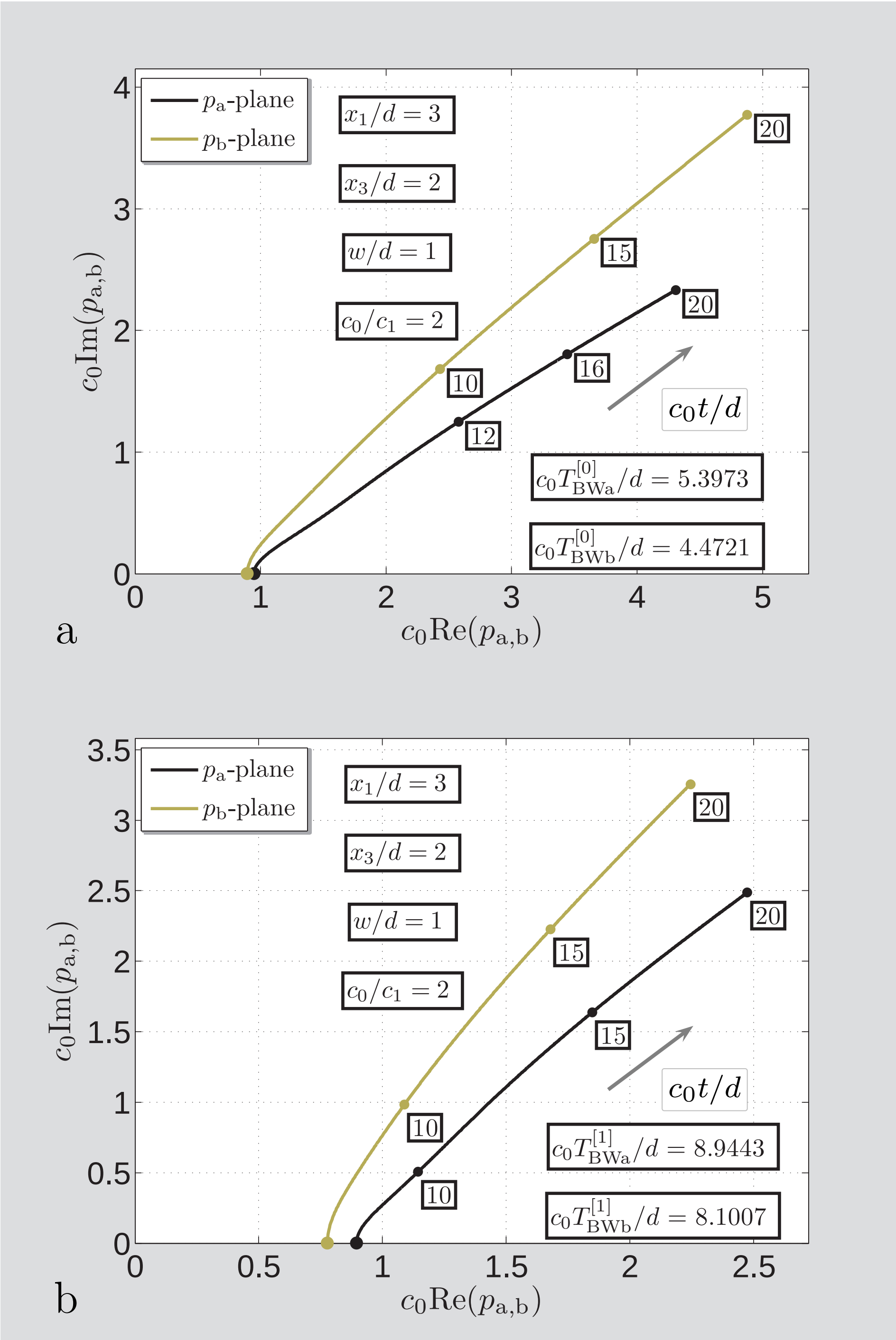


Figure 3.10: Examples of Cagniard-DeHoop contours associated with the first two successive time-domain constituents in vacuum (a) $n = 0$; (b) $n = 1$.

Chapter 4

Conclusions

Currently used computational tools are not up to the demands that came up with the recent advances in the communication systems. Realizing the lack of the pulsed-field computational tools, we have developed one for the exact time-domain analysis of some typical radiators used in antenna arrays. The applied approach is entirely built upon the space-time description and does not introduce any mathematical artifacts that follow from frequency-domain descriptions. As it turned out, the developed pulsed-field computational tool provides the capabilities that lie far beyond the scope of currently used software instruments. The most striking feature is the possibility of the exact evaluation of all excited pulsed electromagnetic field components at a given observation point within a finite time-window. The obtained results have proved to be applicable to the design of the antenna arrays with agile beam steering and beam shaping facilities.

To accommodate the identified objectives of the thesis, we have employed the Cagniard-DeHoop technique. It has been demonstrated that this technique is capable of providing the exact time-domain closed-form expressions that give physical insights into the radiation mechanism, which is necessary for the efficient design process in practice. These results thus form the solid fundamental basis for novel *time-domain* applications of antenna arrays.

Throughout the thesis, the pulsed electromagnetic field excited by controlled aperture source distributions is investigated in various problem configurations. The common feature of the solution of all problems is the development of the generic integral representation for the radiated electromagnetic field components, which significantly contribute to the brevity and lucidity of the thesis. The handling with generic integral representations can be designated as the theoretical cornerstone of the thesis. Most of the chapters are supplemented with numerical examples that clearly illustrate the main features of a pertinent problem in hand.

In Chapter 3 the pulsed electromagnetic field radiation from the narrow slot has been adressed. Chapter provided more ways for solving the problem and, thus, helped the reader to understand the approach applied troughout the thesis.

Chapter 4 aimed at the investigation of the pulsed electromagnetic radiation from the narrow slot antenna in the presence of the additional perfectly electrically conducting screen. This chapter has illustrated how to accommodate the reflected time-domain constituents pertinent to the narrow slot antenna.

In Chapter 5 the pulsed electromagnetic radiation from the narrow slot with the dielectric covering was investigated. It has been shown that the applied approach is capable of describing all intricate phenomena that arise on account of the nonzero contrast in electromagnetic properties above the narrow radiating slot. The obtained exact expressions make possible to design a pulse-excited antenna array of narrow slots taking into account the influence of the protecting dielectric covering.

From Chapter 6 on, the more realistic aperture radiators, with a finite slot width, are considered. For this type of radiating apertures, it was demonstrated that the excitation via a wide slot shows additional features in that the corners show a separate diffractive behavior with accompanying wavefronts. Chapter 6 has described the pulsed radiation behavior of the free-standing wide slot and served as the point of the departure for the following chapters. Here, it has been demonstrated how the obtained results can be used for the design of a pulsed-field antenna array.

Chapter 7 focused on the analysis of the pulsed electromagnetic radiation from the wide slot antenna in the presence of the additional perfectly electrically conducting screen. This chapter has illustrated how to deal with the reflected time-domain constituents pertinent to the wide slot antenna.

In Chapter 8 the pulsed electromagnetic radiation from the wide slot with the dielectric covering was investigated. It has been shown that the applied approach is capable of describing all intricate phenomena that arise on account of the nonzero contrast in electromagnetic properties above the wide radiating slot. The obtained exact expressions make possible to design a pulse-excited antenna array of wide slots taking into account the influence of the protecting dielectric covering.

Chapter 9 concerned the handling of a nonuniform excitation field distribution, which can be applied on all previous problem configurations with the wide slot. It has been shown that the modal excitation can be easily taken into account at the expense of having to evaluate an additional one-dimensional integral over a finite interval. The provided numerical examples have demonstrated how the spatial changes in the modal excitation manifest themselves in the time-domain responses of the radiated field components.

The prospective developments and the course of the future research rest in a generalization of our approach for three-dimensional radiators and in the applications of the obtained results. In this respect, we can provide the following examples:

- The description of the interaction of the analyzed aperture antenna array and a scatterer through the time-domain field/source reciprocity theorem and a development of pulsed-field radar identification methods.
- The analysis and design of time-domain near-field focused antenna arrays.
- The design and optimisation of wireless integrated circuits interconnects.

Having pinpointed some of the future scientific targets, we conclude the thesis.

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A. T. De Hoop, M. Stumpf and I. E. Lager, "Pulsed electromagnetic field radiation from a wide slot antenna with a dielectric layer," submitted to *IEEE Transactions on Antennas and Propagation*, 2010.

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M. Stumpf, A. T. De Hoop and I. E. Lager, “Closed-form time-domain expressions for the 2D pulsed EM field radiated by an array of slot antennas of finite width,” in *Proc. International Symposium on Electromagnetic Theory*, URSI Commission B, Berlin, pp. 786–789, August 2010.

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