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M. N. LEGENKIY AND A. YU. BUTRYM
V. Karazin National University of Kharkiv,
4, Svoboda Sq., Kharkiv, 61022, Ukraine
E-mail: MLegenkiy@ya.ru, AButrym@ya.ru

EXCITATION AND PROPAGATION OF A FAST PULSE GUIDED WAVE IN A CIRCULAR DIELECTRIC WAVEGUIDE

It is shown that a pulse signal in a circular dielectric waveguide is partitioned into slow and fast waves. The fast wave propagates along the dielectric surface with the speed of light in free space and creates a precursor field in the dielectric waveguide in the form of cones similar to Cherenkov radiation. These cones are re-reflected at the critical angle between the dielectric interfaces creating a rhombus-shaped wave structure. Long time modeling of this fast wave has been conducted using the Moving Frame Body of Revolution FDTD technique (BOR-FDTD). The revealed peculiarities of the considered wave structure are discussed.

Keywords: dielectric waveguide, pulse wave, Time Domain, precursor, BOR-FDTD, moving frame technique

1. Introduction

Propagation of transient electromagnetic waves in optical (dielectric) waveguides has not yet been sufficiently studied. Whereas increasing the communication channel capacity requires adequate modelling of propagation of short pulses in such waveguides. In this paper, we are going to reveal physical processes that occur with excitation and propagation of short pulse signals in optical waveguides. Special emphasis will be given to long time modelling of the precursor wave directly in the Time Domain (TD).

Harmonic wave propagation in dielectric waveguides is well studied with the Frequency Domain (FD) methods [1]. In this case, the sought field in the structure is considered as a set of uncoupled modes. There is a discrete spectrum of guided wave modes, for which the field is localized within the rod. In order to describe the fields near the sources, the continuous spectrum of modes which are localized in the whole space around the dielectric rod should also be taken into account. Near the sources, there can exist such interesting phenomena as excitation of leaky modes [2] and complex modes [3].

Propagation of pulse signals in a dielectric waveguide is much less studied. Certainly, such a problem can be treated in the FD. In this case, the signal is presented as a Fourier integral, each frequency component of the field can be expanded into the modes at the corresponding frequency and propagated at any distance with the corresponding propagation constants for each mode. However, all the mode configurations and propagation constants depend on frequency. As a result, the field energy will be spread among modes and frequency spectrum in a non-factorable manner. After applying the inverse Fourier transform in such an approach, the resulting signal will not keep behavior of the separate modes, and the corresponding physical effects known for harmonic signals cannot be observed for pulse waves, whereas new phenomena not seen from the FD point of view can be revealed. Thus, it is of interest to consider the physical processes of excitation and propagation of pulse waves directly in the TD in order to look for some new effects related to pulse nature of the fields.

Several papers consider pulse propagation along the dielectric boundary, mainly in the analysis of diffraction by dielectric cylinders. At that, different authors use rigorous analytical FD techniques [4, 5], approximate techniques like geometric optics [6], purely numerical methods like FDTD/PSTD [7], and experimental measurements [8]. It will be observed that for calculation in FD, some approximations and simplifications are used in order to avoid the above mentioned problem of non-factorable mode-frequency separation. For example in [4], some technique with the so-called Airy phase is used in order to restrict calculations to the FD modes that are assumed to contribute most to the pulse wave guided part. As a consequence, the calculation results are reported to have significant discrepancy as against the experimental ones.

2. Calculation Method

In this study, in order to calculate the field distributions at different time instants in a circular dielectric waveguide with constant permittivity, the BOR-FDTD (Body of Revolution Finite Difference in Time Domain) method is used. The sought fields are expanded into series over the independent angle harmonics [9]. This allows transforming 3D Maxwell equations to 2D problem in cylindrical coordinates ρ, z for independent angle modes (the case of axisymmetric mode $m=0$ is used below in numerical examples). Applying the finite difference approximation to the equations, the updating formulas for field calculation in consecutive time instants can be derived. This procedure is described in book [9] in detail. This numerical scheme requires some conditions observed to limit the calculation domain. Such conditions should model the surrounding free space and the semi-infinite waveguide parts ahead and behind the computational domain. In this work, the Perfectly Matched Layer (PML) conditions proposed in [10] are used. The PML boundary (10 radial cells thick) gives the error less than 0.15 % and does not affect the calculation results essentially. Verification of this BOR-FDTD algorithm is provided in paper [11] by comparing with the TD modal basis method.

To consider a long time behavior of the pulse field in a dielectric waveguide, the method described is complemented with a Moving Frame technique (MF) [12]: calculations are made not in the whole space where the wave is spread out but only in some constant size frame that propagates with the field wavefront at some constant speed (in our case – with the speed of light in free space c_0). For implementing this technique, an integer ratio of time step (Δt) to cell size (Δz) should be taken, in our case it is $2c_0\Delta t = \Delta z$, providing a stable calculation scheme for the zero angular harmonic [9]. Thus, after each two time steps, all the fields in the computational domain are shifted backwards by one cell. Ahead of the computational domain, one-cell thick layer with the zero fields is added. It does not disturb the solution since the wave is unable to reach this region due to the finite speed of the electromagnetic field propagation. The fields in the trailing cells are not updated since the error due to their not updating will go out of the frame at the next step and thus will not disturb the solution in the frame moving at the speed of light c_0. The error with using the MF technique is estimated to be less than 0.4 % in our case; it is caused by superluminal propagation of disturbances from the back cells due to inherited numerical dispersion of the finite difference scheme [9].

3. Discussion of Numerical Results

We have considered the pulse wave propagation in a circular dielectric waveguide with constant dielectric permittivity profile. Some results on this topic were published earlier in papers [11, 13, 14]. In this paper, we are going to discuss the related terminology for describing the revealed wave phenomena and some new results.

The wave is launched by a ring with circulating magnetic current inside the dielectric rod, the source was chosen with the waveform of Gaussian derivative with the central frequency of $f_m \approx 1.89\, c_0/a$, where a is the rod radius, the current ring radius being $a/2$. Thus, we have a localized source inside the dielectric, its field can be presented as a number of rays (plane wave decomposition). These rays diffract at the boundary in accordance to Fresnel formulas.

If the ray incidence angle is less than the critical one $\left(\theta_{cr} = \arcsin(1/\sqrt{\varepsilon})\right)$, some part of its energy transmits through the boundary and radiates into free space (see the Radiated Wave (RW) in Fig. 1), the rest of the energy reflects back into the dielectric, and the process repeats after the remaining wave approaching the opposite boundary (see the second RW pulse group in Fig. 1). The RW propagates like a spherical wave out of the place where the source is positioned.

For the rays with an incidence angle larger than the critical angle, the total reflection occurs, the wave is re-reflected into the dielectric, thus forming the Guided Wave (GW) being similar to the well-known guided modes in FD. This wave propagates inside the dielectric along the rod re-reflecting between the opposite waveguide boundaries. These rays propagate at a small angle to the axis and are localized in time, the speed of this wave group is close to the speed of light in the dielectric medium $c_0/\sqrt{\varepsilon}$ (see arrow 1 in Fig. 1).

The rays with the incidence angles around the critical angle create some wave outside the rod that looks similar to the well-known in FD surface wave (which propagates along the rod and decays off the waveguide). However, in contrast to the FD surface wave, this wave propagates along the rod with the speed of light in free space c_0 (arrow 2 in Fig. 1), thus it will be misleading to call it a "surface wave" which is always a slow one. Also, this wave creates some radiation with the inclined wave front inside the dielectric rod; due to this, the wave loses energy in

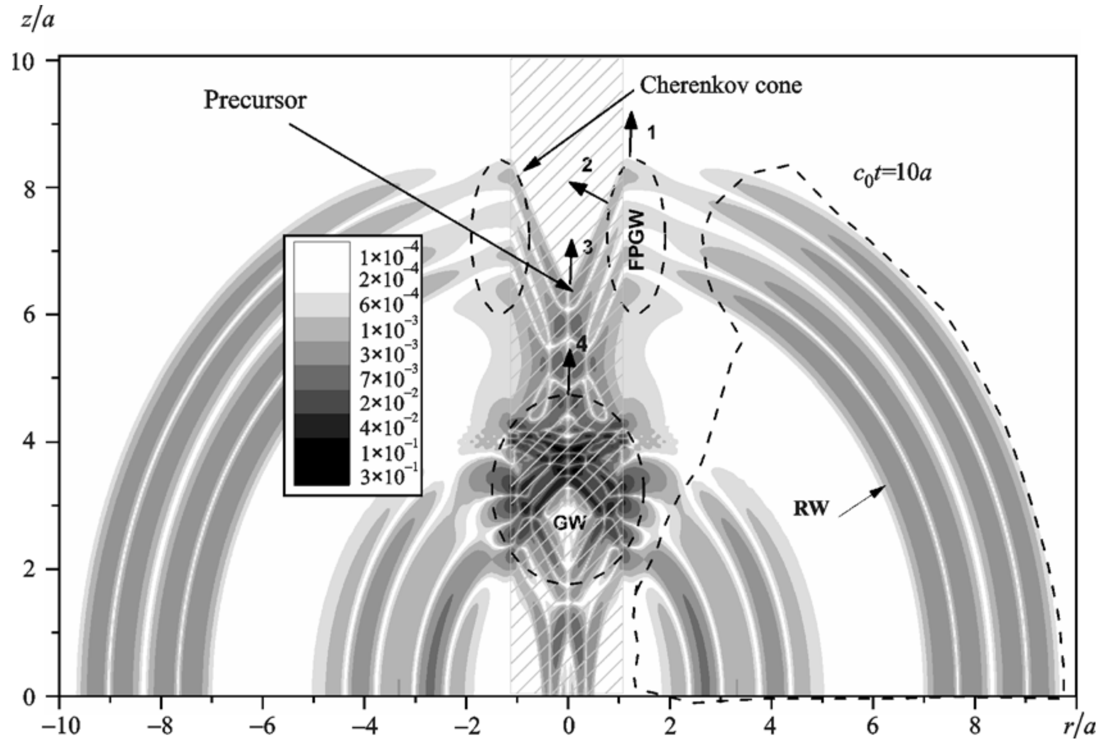

Fig. 1. Spatial distribution of electric field magnitude in the circular dielectric waveguide with $\varepsilon = 5$ at some time instant

propagation. This phenomenon is similar to the Cherenkov effect: the wave propagates in free space with speed c_0 and its footprint on the interface creates radiation inside the medium where electromagnetic waves travel at low speed $c_0/\sqrt{\varepsilon}$. As a result, there exists a converging conical wave inside the rod. The wave front of this conical wave propagates with the speed of light in the dielectric in the direction normal to the front (arrow 3 in Fig. 1), while the crossing point at the rod axis propagates with the speed of light in free space (arrow 4 in Fig. 1) along the waveguide axis. The described effect is similar to scissors: the blades propagate slower than the cutting line. The converging conical wave after passing the axis transforms into a diverging conical wave which then impinges onto the dielectric interface at the same critical angle, thus giving rise to the next pulse of the "surface wave". This pulse, in turn, forms a converging cone, and the process repeats creating a rhombus like wave structure (see Fig. 2). Thus, on its way this wave structure grows along the axis: there occur new rhombi behind. As a result, we have a pulse precursor in the form of cones inside the rod with small "wings" outside it, the structure as a whole propagates ahead the usual GW in the dielectric waveguide at speed c_0.

A similar phenomenon was described in paper [4] where the author considers pulse radiation from a horizontal electric dipole (HED) placed on a homogeneous dielectric half-space. In this case (see Fig. 3), there is a spherical wave in free space (A), which creates some track with inclined wave front (D) in the dielectric medium. And similarly, the spherical wave in the dielectric (B) creates the track in free space (C), though this wave as if comes up with the source wave (B) due to difference in the velocities in the media.

Fig. 1 shows the field picture shortly after the wave was launched. Using the aforesaid MF BOR-FDTD technique we are able to calculate the long time wave propagation in the dielectric waveguide. Several consecutive frames of this simulation are shown in Fig. 2. Here, at the first two shots, the computation frame was standing still (before the wave filled the domain), while at the others, the frame was moving rightward at speed c_0. In subplots a and b in Fig. 2, the beginning of partitioning the pulse wave into the GW, RW, and precursor wave can be seen. The RW emerges near the source and propagates into free space in a spherical wave manner. After the computation frame starts moving (Fig. 2(c) – 2(h)) the front part of the wave (precursor) seems to be "frozen", its frame-

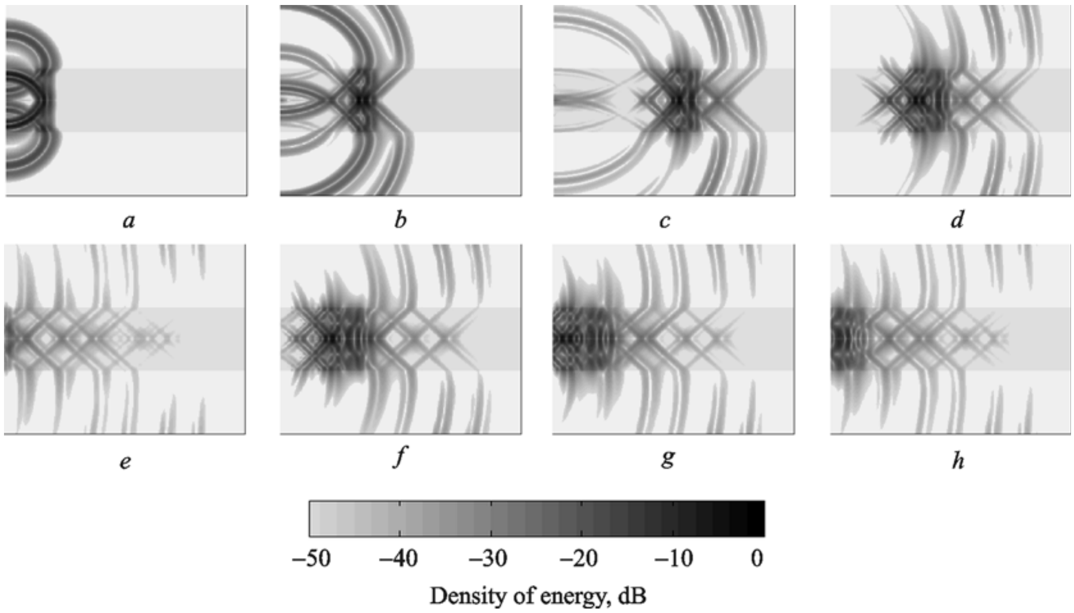

Fig. 2. Spatial distribution of electromagnetic energy density in the dielectric waveguide ($\varepsilon = 5$) at several time instants (*a*, *b* – still frame; *c*–*h* – moving frame; the horizontal strip in the middle depicts the dielectric core region)

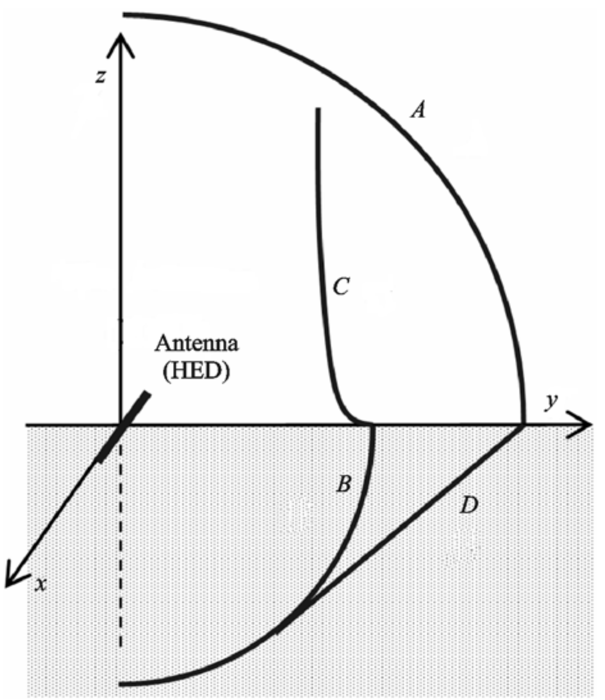

Fig. 3. Simplified view of radiation from a horizontal electric dipole (HED) placed on a homogeneous dielectric half-space. *A* and *B* are spherical waves in air and ground, respectively; *C* and *D* are waves generated in air and ground which match *B* and *A*. (The Figure is plotted after [4], cited from Annan, 1973)

work (intensity distribution ridges) is not changed with time. Thus, the precursor propagates along the waveguide with the frame velocity c_0 as a whole wave structure. Whereas its amplitude slowly decays with propagation due to the energy spreading over the growing length of wave structure. Numerical experiments reveal that the amplitude of the peaks in the precursor wave structure decays with time as t^{-2}. Changing the rod permittivity affects only the angle which the cones form with the axis, whereas all other peculiarities of the precursor remain the same: it propagates as a whole structure at speed c_0 with amplitude of the peaks decaying as t^{-2}.

4. Concluding Remarks

It has been revealed that under pulse excitation there occurs a pulse precursor in a dielectric waveguide that looks like a pulse wave formed by Cherenkov cones re-reflection between the dielectric boundaries at the critical angle and some perpendicular "wings" decaying off the rod. This wave structure propagates in the dielectric waveguide at the speed of light in free space and forms a rhombus like distribution of the field. Though it is definitely a wave structure, it cannot be considered in terms of traditional "waveguide modes" since the latter by definition should keep some cross-sectional configuration along the axis. In our previous publications, we have called such a wave as Pulse Surface Wave. However, it is clear that the wave energy is contained not only in the outer surface part but in the inner rhombic structure, too. Using the term "surface wave" in this situation seems to be misleading, therefore we propose to name this wave as a Fast Pulse Guided Wave (FPGW). This wave propagates at the speed of light in the surrounding medium. It is a pulse wave and can be observed only in the transient case. Also, it is a guided one and is confined within the rod and propagates along this latter. Some part of this wave propagates outside the rod along the boundary. It decays in propagation due to energy spreading along the waveguide axis. Thus, formally speaking, its "group" velocity considered as the speed of propagation of the wave energy center should be less than the "phase" velocity that can be formally considered as the speed of propagation of the local maxima, which has been observed to be equal to the speed of light in free spase thus being "frequency independent". This consideration is rather formal due to the terminology originating from the FD, while the phenomenon is "revealable" only from TD point of view.

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М. Н. Легенький, А. Ю. Бутрым

Харьковский национальный университет имени В. Н. Каразина, пл. Свободы, 4, г. Харьков, 61022, Украина

ВОЗБУЖДЕНИЕ И РАСПРОСТРАНЕНИЕ БЫСТРОЙ ИМПУЛЬСНОЙ ВОЛНОВОДНОЙ ВОЛНЫ В КРУГЛОМ ДИЭЛЕКТРИЧЕСКОМ ВОЛНОВОДЕ

Продемонстрировано разделение импульсного сигнала в диэлектрическом волноводе на медленную и быструю волны. Быстрая волна распространяется вдоль поверхности диэлектрика со скоростью света в свободном пространстве и создает предвестник в волноводе в виде конусов, похожих на излучение Черенкова. Эти конусы переотражаются между границами диэлектрика под углом полного внутреннего отражения, создавая ромбическую волновую структуру. Проведено долговременное моделирование этой быстрой волны с использованием метода конечных разностей во временной области для тел вращения в сопровождающем окне. Обсуждаются выявленные особенности поведения рассмотренной волновой структуры.

М. М. Легенький, О. Ю. Бутрим

Харківський національний університет імені В. Н. Каразіна, пл. Свободи, 4, м. Харків, 61022, Україна

ЗБУДЖЕННЯ ТА ПОШИРЕННЯ ШВИДКОЇ ІМПУЛЬСНОЇ ХВИЛЕВОДНОЇ ХВИЛІ У КРУГЛОМУ ДІЕЛЕКТРИЧНОМУ ХВИЛЕВОДІ

Продемонстровано розділення імпульсного сигналу в діелектричному хвилеводі на повільну та швидку хвилі. Швидка хвиля поширюється вздовж поверхні діелектрика зі швидкістю світла у вільному просторі та створює передвісник у хвилеводі у вигляді конусів, схожих на випромінювання Черенкова. Ці конуси перевідбиваються між границями діелектрика під кутом повного внутрішнього відбиття, утворюючи ромбічну хвилеву структуру. Виконано довгочасове моделювання цієї швидкої хвилі методом скінченних різниць у часовій області для тіл обертання у супроводжуючому вікні. Дискутуються виявлені особливості поведінки розглянутої хвилевої структури.

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