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PULSE SIGNALS IN OPEN CIRCULAR DIELECTRIC WAVEGUIDE

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Abstract—Excitation and propagation of a pulse electromagnetic wave in an open circular dielectric waveguide is considered. Partition of the pulse field into radiated wave, surface wave, and guided wave has been revealed and the corresponding physical effects are interpreted directly in the time domain. Namely it was shown that there is a precursor at the rod axis that propagates with speed of light in free space. It originates from the pulse surface wave that propagates along the rod surface and radiates into the rod in a Cherenkov like manner.

1. INTRODUCTION

One of the main trends in communications recently consists in increasing channel capacity by exploiting ultrawideband short pulses. Among transmission lines that are of high interest in communications are optical fibers (dielectric waveguides). Propagation of ultrashort electromagnetic pulses in such lines has not been studied sufficiently yet. So it is of interest to consider physical processes that occur with excitation and propagation of pulse signals in open dielectric waveguides. This problem is also met in analysis of pulse radiation from a rod antenna.

Harmonic wave propagation in dielectric waveguides is well studied in the Frequency Domain (FD) [1]. In this case the sought field in the structure is presented as a set of uncoupled modes. There are guided wave modes that have field localized within the rod, the spectrum being discrete. These modes are used for transmitting information. In describing fields near the sources one also needs to

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consider continuous spectrum of modes that describe radiated field. In the vicinity of sources there are also such interesting phenomena as excitation of leaky modes [2] and complex modes [3].

Nevertheless propagation of pulse signals in dielectric waveguides is much less studied. Surely such a problem can be treated in the frequency domain. That is the signal can be presented as a Fourier integral, each frequency component of the field can be expanded into the modes at that frequency and propagated at any distance with properly calculated propagation constants for each mode. However all the mode configurations and the corresponding propagation constants are frequency dependent. As a result the field energy will be spread among modes and frequency spectrum in non factorable manner. After applying inverse Fourier transform in such an approach the resulting signal will not keep behavior of separate modes, and the corresponding physical effects known for monochromatic signals will not be observed in pulse waves. So it is of interest to consider these physical processes directly in the time domain in order to reveal some new effects, which are relevant to pulse nature of the fields.

There are several papers that consider pulse propagation along dielectric boundary, mainly in analysis of diffraction by dielectric cylinders. At that different authors use rigorous analytical frequency domain techniques [4, 5], approximate techniques like geometric optics [6], purely numerical methods like FDTD/PSTD [7], and experimental measurements [8]. It should be noted that in describing pulse surface waves different authors assume controversial models regarding surface wave speed. Moreover in the frequency domain calculation techniques some approximations and simplifications are unavoidable. For example in [4] some technique with so called Airy phase is used in order to restrict calculations to the FD modes that are assumed to contribute most to the guided part of the pulse wave. At that the calculation results are reported to have significant discrepancy compared to the experimental ones.

In this paper we are going to study the effects appearing in process of excitation of a pulse wave by sources that are located inside a dielectric rod. The calculation method is based on using mode expansions in time domain over some set of coupled frequency-independent modes. This calculation technique is briefly described in conference paper [9]. Description of the method is not among the aims of the current paper. It is sufficient to say that its results were compared against direct FDTD calculations and the discrepancies were less than intrinsic errors of finite difference approximation.Being a time domain method it allows obtaining the waveforms, and as a result the information at all the frequencies is available after single simulation.

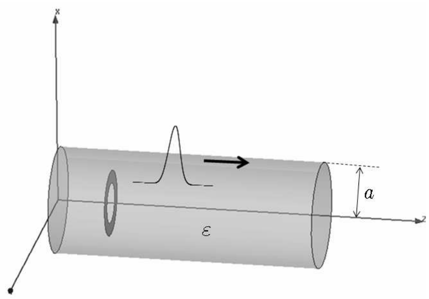

Figure 1. Circular dielectric waveguide.

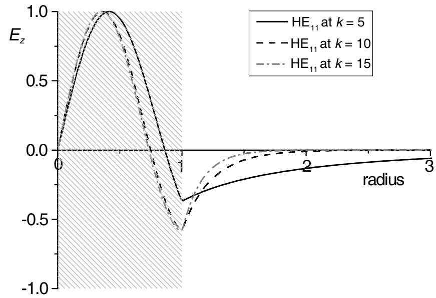

Figure 2. FD modes.

Also we needn't make any assumptions like that in [4] caused by using frequency dependent modes. More detailed description of the method and some additional results will be published later as a separate paper. Here we concentrate on discussion of the physical results revealed during numerical modeling of the process.

2. PROBLEM STATEMENT

Let's consider a circular dielectric waveguide with radius a and permittivity ε (see Figure 1). The ambient medium is air. The waveguide is infinite in both directions along axis z. It is excited by a ring of azimuthal magnetic currents that allows effectively launching the principal FD mode (HE_{11}, see Figure 2) in such a structure in a wide frequency band [10]. The time waveform of the excitation currents was chosen to be Gaussian with spatial duration equal to 2/5 of rod radius a. The radial distribution of the currents was also chosen with Gaussian spatial shape in order to avoid excitation of unphysical sharp wave front edges:

$$\begin{aligned}\hat{\vec{J}}(r,\varphi,z,t) &= \vec{\varphi}_0 \cos(\varphi)\delta(z-z_0)\exp\left(-((r-r_0)/\delta r)^2\right)\\ &\quad\cdot\exp\left(-((t-t_0)/T)^2\right)\\ r_0 &= a/2,\ \delta r = 0.12a,\ c_0 T = a/5,\ t_0 = 5T\end{aligned} \tag{1}$$

r, φ, z are cylindrical coordinates, $\delta(\cdot)$ is Dirac delta function, c_0 is the speed of light in free space, δr is the radial spread of the current ring, r_0 is the average ring radius, T is the time half duration of the pulse, t_0 is the time center of the excitation pulse, hat over J means that it is magnetic current density. Such source launches a pulse electromagnetic wave symmetrically in $\pm z$ directions.

3. RESULTS OF NUMERICAL CALCULATIONS

Using the above mentioned computational technique we obtained several space-time field distributions to analyze. In Figure 3(a) one can see the field distribution at the dielectric rod axis in z-t coordinates. Next to it similar plots are shown for field distribution in free space and in a closed hollow circular waveguide with radius a under the same excitation. In free space (Figure 3(b)) a single radiated pulse is moving away from the source without any reflections at speed c_0. In this case the source forms a diverging spherical wave with amplitude that decreases at the axis as r^{-1} (transient dipole radiation in free space [11]). For the closed waveguide (Figure 3(c)) the picture is more complicated: the pulses reflect from the waveguide walls and create at

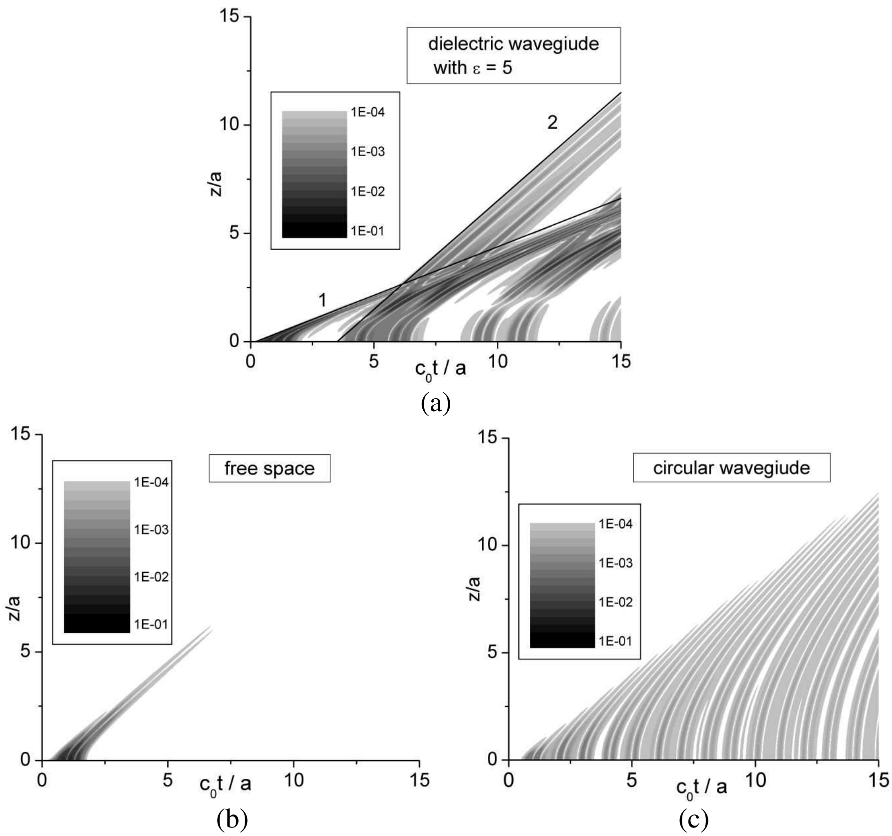

Figure 3. Amplitude distribution of longitudinal electric field component in z-t coordinates at z-axis (a) for dielectric rod with $\varepsilon = 5$, (b) for free space, and (c) for closed hollow circular waveguide.

the waveguide axis a complex field distribution consisting of a series of hyperbolae. In Figure 3(a) for the dielectric waveguide we can see a mix of the two above distributions: there are precursors (line 2) traveling at speed c_0 and hyperbolae that have asymptotic (line 1) corresponding to speed of light in the dielectric $c = c_0/\sqrt{\varepsilon}$. Such a picture is formed due to reflections at the dielectric interface. In contrast to the closed waveguide we can see some zero-field zones at the hyperbolae that are caused by full transmission at Brewster's angle (the magnetic ring sources create p-polarized fields at the dielectric interface).

Appearing of the precursors at the dielectric rod axis is explained by leakage from the surface wave that propagates along the dielectric interface at the speed of light in free space. This effect is more clearly seen in Figure 5 where we present the spatial distribution of the pulse field at time instant $c_0t = 10a$ (shaded area delimits the dielectric rod region). Here one can see surface waves (SW in the figure) that propagate along the surface at speed c_0 (arrow 1). It creates a Cherenkov like radiation [12] into the rod (arrow 2). The front of the Cherenkov radiation propagates inside the rod at speed of light in the dielectric $c = c_0/\sqrt{\varepsilon}$ (arrow 2), while the crossing point at the rod axis propagates with speed c_0 (arrow 3) that appears as line 2 in Figure 3(a).

We should especially highlight the difference between the commonly known in FD surface waves and the pulse surface waves we met here. In FD there may exist surface waves at lossy dielectric boundary (so called "surface plasmons") that decay exponentially both down and up the dielectric surface and propagates along the surface at slow speed with relatively small decay [13]. In a lossless dielectric waveguide there exist guided waves that are localized inside the rod and also decay exponentially off the surface (see Figure 2), these waves propagate without losses at slow speed. As it was discussed above in TD we can observe a different phenomenon: a surface wave that propagates with the speed of light in free space and decay with propagation due to leakage into the dielectric. A similar effect was considered by Annan in 1973 [14]: a horizontal dipole on dielectric surface excites a spherical wave front in the air, which creates a flat front in the dielectric halfspace by its footprint on the surface. In contrast to Annan we placed the sources inside the dielectric medium, so the spherical front in the air is partitioned due to total internal reflection effect into a radiating part (RW in Figure 5) and a surface wave with a gap between them.

The considered surface wave loses energy due to Cherenkov radiation into the dielectric. The pulse surface wave is excited by rays from the source that arrive to the dielectric interface at angles near the

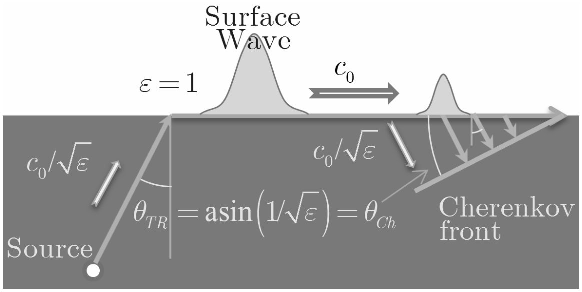

Figure 4. Evolution of the surface wave.

critical angle of total reflection $\theta_{TR} = \mathrm{asin}(1/\sqrt{\varepsilon})$ (see Figure 4). It is interesting to note that the Cherenkov front is formed by the rays that penetrate into the dielectric at the same critical angle. Thus the angle between the Cherenkov front and the surface is the same $\theta_{Ch} = \theta_{TR}$ (see Figure 4). In the limit of $\varepsilon \to 1$ we have the total reflection angle becoming grazing $\theta_{TR} \to \pi/2$ and the Cherenkov front tends to be perpendicular to the surface. In contrast for high ε the total reflection occurs at nearly normal angles while the Cherenkov front leans to the very surface.

It is interesting to discuss different considerations regarding the speed of a pulse surface wave in early publications on the subject. In experimental study of pulse wave diffraction at a lossy dielectric cylinder (alumina at terahertz frequencies) [8] a surface wave speed was measured to be $0,91c_0$ (this speed apparently differs from c_0 because of losses and surface curvature). In [6] the authors when considering a geometrical optics model of pulse scattering at a lossless dielectric cylinder assumed the velocity of surface waves to be equal to the velocity of the fastest medium. In [5] the authors study diffraction of a pulse wave on a dielectric sphere, at that the surface waves that contribute to the backscattering have propagation constant closer to that in dielectric rather than in the free space due to effect of short cutting across the sphere. It should be noted that in our case the pulse wave propagates in a regular waveguide where there are no losses and no curvature along the propagation direction, so we observe the speed of the surface wave to be equal to c_0.

Besides the surface wave one can also observe in Figure 5 the Guided Wave (GW) that propagates along the dielectric rod at slow speed $c = c_0/\sqrt{\varepsilon}$ (arrow 4). This wave is formed by the rays that arrive from the source onto the surface at angles larger than the total reflection angle $\theta > \theta_{TR}$ and thus they stay localized within the dielectric core propagating mainly along the axis. These rays form the hyperbola structure shown in Figure 3. In Figure 3(c) one can see

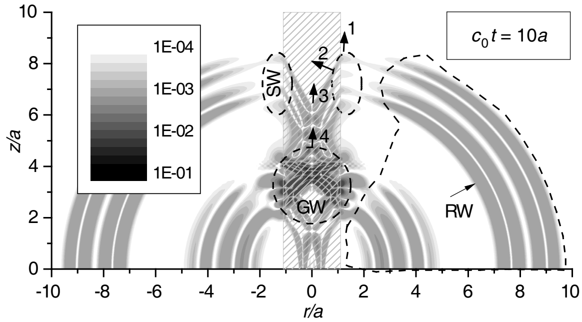

Figure 5. Distribution of longitudinal electric field component in r-z coordinates at time instant $c_0t = 10a$ for dielectric rod with $\varepsilon = 5$.

the hyperbolae that correspond to the rays reflecting from the closed waveguide boundary; in contrast in Figure 3(a) there are white spaces between such hyperbolae that correspond to the rays that penetrate through the boundary and doesn't participate in forming the guided wave. Such rays propagate outside the core and form the Radiated Wave (RW) shown in Figure 5. This wave is similar to radiation of a transient dipole [11], in the far zone it looks like a spherical wave with angular distribution defined by dipole nature of the source, which is additionally effected by angular dependence of Fresnel coefficients and ray direction changing at refraction. The part of the wave that reflects back from the dielectric surface forms the subsequent RWs (second wave packet in RW in Figure 5). The radiated part of the wave has spherical front, though the front is slightly distorted because the rays pass different optical distances (in dielectric core) in different directions.

It is interesting to note that the first group of the RWs consists of two bipolar pulses, while the subsequent pulses are mainly unipolar ones. It can be more easily explained with the help of r-t field distribution shown in Figure 6. Here one can see that the first bipolar pulse is formed by the upper part of the source ring, while the second bipolar pulse is created by the bottom part of the magnetic current ring. The subsequent radiated pulses are caused by the fields that reflect from the boundary, pass through the dielectric core center (caustic of the converging cylindrical wave) and then escape through the dielectric boundary. On this way the cylindrical wave undergoes strong dispersion, especially near the caustic, as a result the waveform structure of the pulse changes significantly. Propagation speed in the rod for Figures 6(a) and 6(b) is $c_0/\sqrt{\varepsilon} \approx 0,3c_0$ for $\varepsilon = 12$ and $c_0/\sqrt{\varepsilon} \approx 0,45c_0$ for $\varepsilon = 5$ correspondingly.

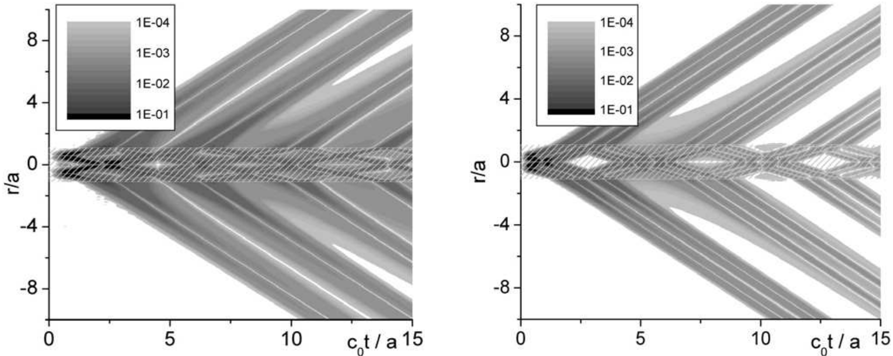

Figure 6. Distribution of longitudinal electric field component in r-t coordinates at cross-section $z = 0$ for dielectric rod with (a) $\varepsilon = 12$ and (b) $\varepsilon = 5$.

4. CONCLUSIONS

We have analyzed a short pulse excitation and propagation in a circular dielectric waveguide. Some effects of pulse wave propagation in such a structure were first described and interpreted. From analysis of the physical processes we revealed a pulse surface wave that is created by the rays from the source incident under total reflection angle onto the dielectric surface. This wave propagates at the speed of light in free space and loses energy on creation of Cherenkov like radiation into the dielectric. The Cherenkov radiation propagates inside the dielectric at the same angle of total reflection. This radiation creates precursors at the rod axis that propagates along the rod with the speed of light in free space. We also analyzed structure of the field radiated into free space in the form of spherical waves. It was shown that the waveform of the subsequent radiated pulses can be changed significantly after crossing the caustic of the converging cylindrical wave due to strong dispersion. Thus in the analyzed case we observed two bipolar pulses in the first radiated wave and mainly monopolar pulses in the subsequent waves. Some peculiarities of the hyperbolic structure of the pulse wave on z-t diagram have been explained for the dielectric waveguide.

In the paper to follow we are going to provide a detailed description of the used computational technique, which is based on exploiting mode expansion in time domain. Also we are going to analyze long time behavior of precursors in the considered structure caused by effects of re-excitation of the surface wave by the described Cherenkov front.

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