

## Isolation of two-dimensional E-fields in the excitation equations for hollow waveguides

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Received on July 9, 2016

**Abstract:** *The traditional excitation equations of the Vainshtein waveguide excitation theory based on presenting the field excited by extraneous sources as a sum of TE and TM eigenwaves of the hollow waveguide, which transversal components form the complete basis in the class of the transversal vectors of a waveguide section. However, in the excitation sources area (longitudinal sonde, electron beam) the waveguide is not hollow and the potential transverse electric field appears in this area. The transversal electric field completes the basis of TE and TM waves. This is not taken into account in the traditional excitation equations. In this paper, the necessary correction of the excitation equations in the sources area is obtained.*

**Keywords:** *Vainshtein waveguide excitation theory, excitation equation, electron beam.*

**For citation (IEEE):** A. A. Kuraev, A. A. Koronovskii, S. A. Kurkin, A. O. Rak, I. S. Rempen, A. A. Badarin, and A. E. Hramov, “Isolation of two-dimensional E-fields in the excitation equations for hollow waveguides,” *Infocommunications and Radio Technologies*, vol. 1, no. 1, pp. 17–28, 2018. doi: 10.15826/icrt.2018.01.1.02.

# Выделение двумерного электрического поля в уравнениях возбуждения для полых волноводов<sup>1</sup>

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Статья поступила 9 июля 2016 г.

**Аннотация:** Хорошо известно, что уравнения возбуждения волноводов Л. А. Вайнштейна основываются на возбуждении сторонними источниками тока электромагнитного поля в виде суммы ТЕ и ТМ собственных волн полого волновода, при этом поперечные компоненты образуют полный базис в классе поперечных векторов секции волновода. Тем не менее, в области источников возбуждения (продольный зонд, электронный пучок) волновод не является полым и в этой области возникает потенциальное поперечное электрическое поле. Поперечное электрическое поле дополняет структуру основных ТЕ и ТМ волн. Это не учитывается в традиционных уравнениях возбуждения. В настоящей работе произведена необходимая корректировка уравнений возбуждения в области источников.

**Ключевые слова:** теория волноводов Вайнштейна, уравнения возбуждения, электронный пучок.

**Для цитирования (ГОСТ 7.0.5—2008):** Выделение двумерного электрического поля в уравнениях возбуждения для полых волноводов / Кураев А. А., Короновский А. А., Куркин С. А., Рак А. О., Ремпен И. С., Бадарин А. А., Храмов А. Е. // Инфокоммуникационные и радиоэлектронные технологии. 2018. Т. 1, № 1. С. 17—28.

**Для цитирования (ГОСТ 7.0.11—2011):** Выделение двумерного электрического поля в уравнениях возбуждения для полых волноводов / А. А. Кураев, А. А. Короновский, С. А. Куркин, А. О. Рак, И. С. Ремпен, А. А. Бадарин, А. Е. Храмов // Инфокоммуникационные и радиоэлектронные технологии. — 2018. — Т. 1, № 1. — С. 17—28.

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<sup>1</sup> Статья является расширенной версией доклада, представленного на 24-й Международной Крымской конференции «СВЧ-техника и телекоммуникационные технологии» — КрыМиКо'2014 (Севастополь, РФ, 7—13 сентября 2014 г.).

## 1. Introduction

The development and application of effective semi-analytical or numerical methods for the analysis and investigation of waveguides, resonators and other microwave components in the presence of some sources is an important and actual problem of the modern microwave theory [1–5]. One of such methods is the waveguide excitation theory. The excitation equations of the Vainshtein waveguide excitation theory for regular waveguides [6–8] are widely used in microwave electronics [7–12]. There are a number of problems in this theory. One of them is a representation of static electric and magnetic fields induced by electron beam in a waveguide in the form of solutions to equations of the Vainshtein excitation theory. Other problem solved in this work is the need of several corrections of the waveguide excitation equations in the sources areas. Let us note that the equations of the waveguide excitation theory are based on the representation of the excited field as a sum of TE (E) and TM (H) waves of a hollow waveguide. Their transversal components form a full system in the class of the transversal vectors of a hollow waveguide section. Nevertheless, in the area of a source (a longitudinal sonde, an electron beam) the waveguide contains not a simply connected area of the cross-section but a doubly or multiply connected area, which supposes the existence of the transversal potential electric field. Thus, the basis of TE and TM waves is not complete, and it is necessary to take into account the TEM-wave, since its propagation constant  $\Gamma_T = k = \omega/c$  is not equal to  $\Gamma_V^E$  or  $\Gamma_V^H$  of TM or TE waves ( $\Gamma_V^{E,H} = \sqrt{k^2 - (k_{\perp V}^{E,H})^2}$ ) and it is orthogonal to all TE and TM fields of a hollow waveguide [6–8]. In other words, it cannot be represented using the TM and TE basis of a hollow waveguide and requires a separate calculation. The separated quasi-static field ( $\omega = 0$ ) determines the main part of the source electric field – 2D transversal field ( $\Gamma_T = \omega/c = 0$ ). The last is especially important for the theory of microwave O- and M-type devices [13], gyroresonance devices [14, 15], semiconductor superlattices in a resonator [16] and so on.

In the present paper, we make the important transformation of the excitation equations for hollow waveguides, in which the transversal electric field of the sources is taken into account.

## 2. Regular waveguide

Let us set the task of the stimulation of regular waveguide by an off-site electric source as following. Firstly, it is necessary to solve Maxwell's equations:

$$\left. \begin{aligned} \operatorname{rot} \vec{H} &= \varepsilon_a \frac{\partial \vec{E}}{\partial t} + \vec{\delta}_{es}, \\ \operatorname{rot} \vec{E} &= -\mu_a \frac{\partial \vec{H}}{\partial t}, \\ \operatorname{div} (\varepsilon_a \vec{E}) &= \rho_{es}, \\ \operatorname{div} (\mu_a) &= 0 \end{aligned} \right\} \quad (1)$$

with the following boundary condition on the waveguide walls:

$$[\vec{n}\vec{E}']_S = 0. \quad (2)$$

Here  $\vec{E}$  and  $\vec{H}$  are the electric and magnetic components of the waveguide field;  $\varepsilon_a$  and  $\mu_a$  are the dielectric and magnetic permittivities of the waveguide filling;  $\vec{\delta}_{es}$  and  $\rho_{es}$  are the vector of current density and the space charge density of the off-site electric sources;  $\vec{n}$  is the waveguide wall normal. Condition (2) fits the perfectly conducting walls; it is not hard to make generalization for the occurrence of losses [8].

To find the solution of Eqs. (1) and (2), let us represent the sought field  $\vec{E}$  as two components:

$$\vec{E} = \vec{E}' + \vec{E}'', \quad (3)$$

while  $\operatorname{rot} \vec{E}'' = 0$ . Dividing the field  $\vec{E}$  into  $\vec{E}'$  and  $\vec{E}''$  in equation (3) means that  $\operatorname{div} \vec{E}' \neq 0$  and  $\operatorname{rot} \vec{E}' \neq 0$ . At the same time, the two-dimensional field  $\vec{E}''$  conform to TEM field.

Thereafter the system (1) is divided into two ones:

$$\left. \begin{aligned} \operatorname{rot} \vec{H} &= \varepsilon_a \frac{\partial \vec{E}'}{\partial t} + \vec{\delta}_{es}, \\ \operatorname{rot} \vec{E}' &= -\mu_a \frac{\partial \vec{H}}{\partial t}, \end{aligned} \right\} \quad (4)$$

$$\operatorname{div} \vec{E}'' = \rho_{es}/\varepsilon_a - \operatorname{div} \vec{E}'$$

or

$$\begin{aligned} \nabla^2 \Phi &= -\rho' / \varepsilon_a, \\ \vec{E}'' &= -\operatorname{grad} \Phi, \end{aligned} \quad (5)$$

where  $\vec{\delta}'_{es} = \vec{\delta}_{es} + \varepsilon_a \frac{\partial \vec{E}''}{\partial t} = \vec{\delta}_{es} - \varepsilon_a \frac{\partial}{\partial t} (\operatorname{grad} \Phi)$ ,  $\rho' = \rho - \varepsilon_a \operatorname{div} \vec{E}'$ ,  $\varepsilon_a$  and  $\mu_a$  are constants.

Let us suppose that the waveguide excitation is a stationary process, i.e. the field sources change periodically in time. Then the sought fields  $\vec{E}$ ,  $\vec{H}$  can be represented as Fourier series:

$$\vec{E} = \text{Re} \sum_{n=1}^{\infty} \vec{E}^n e^{jn\omega t}, \quad \vec{H} = \text{Re} \sum_{n=1}^{\infty} \vec{H}^n e^{jn\omega t}. \quad (6)$$

Solutions for  $\vec{E}^n$  and  $\vec{H}^n$  can be written, using the results obtained in Ref. [8], replacing  $\vec{\delta}_{eS}$  by  $\vec{\delta}'_{eS}$ :

$$\left. \begin{aligned} \vec{E}^n &= \dot{C}_S^n \dot{\vec{E}}_S^n + \dot{C}_{-S}^n \dot{\vec{E}}_{-S}^n - \frac{(\vec{\delta}'_z)^n}{jn\omega\epsilon_a}, \\ \vec{H}^n &= \dot{C}_S^n \dot{\vec{H}}_S^n + \dot{C}_{-S}^n \dot{\vec{H}}_{-S}^n \end{aligned} \right\} \quad (7)$$

Here  $\dot{\vec{E}}_{\pm S}^n$  and  $\dot{\vec{H}}_{\pm S}^n$  are the fields of unidirectional (+S) and counter-propagating (-S) inherent waves of the waveguide (without sources) on the frequency  $n\omega$ ,  $(\vec{\delta}'_z)^n$  is the harmonic of z-component of current density  $\vec{\delta}'_z$  on the frequency  $n\omega$ ,  $n > 0$  is the harmonic number.

The coefficients  $\dot{C}_{\pm S}^n$  can be found from the following differential equations:

$$\frac{d\dot{C}_{\pm S}^n}{dz} = \frac{1}{\pi N_S^n} \int_0^{2\pi} \int_{\perp} \vec{\delta}'_z \dot{\vec{E}}_{\mp S}^n dS_{\perp} e^{-jn\omega t} d\omega t, \quad (8)$$

where

$$N_S^n = \int_{S_{\perp}} \left( [\dot{\vec{E}}_{\mp S}^n, \dot{\vec{H}}_{-S}^n] - [\dot{\vec{E}}_{-S}^n, \dot{\vec{H}}_{\mp S}^n] \right) dS_{\perp} \quad (9)$$

is the norm of the wave with S number on the frequency  $n\omega$ ,

$$(\vec{\delta}'_z)^n = (\vec{\delta}_z)^n - jn\omega\epsilon_a \frac{\partial \Phi^n}{\partial z}. \quad (10)$$

Now let us discuss the solution of Eq. (5) representing (6):

$$\dot{\Phi} = \text{Re} \sum \Phi^n e^{jn\omega t}. \quad (11)$$

Hence, using Eqs. (7) and (8) we obtain the following for  $\Phi^n$ :



For TM-type waves we have the following ratio:

$$\begin{aligned}\vec{E}_{-S0t}^n(r_{\perp}^{\rightarrow}) &= -\vec{E}_{-S0t}^n(r_{\perp}^{\rightarrow}), \\ \vec{E}_{-S0z}^n(r_{\perp}^{\rightarrow}) &= -\vec{E}_{-S0z}^n(r_{\perp}^{\rightarrow}), \\ \vec{H}_{-S0t}^n(r_{\perp}^{\rightarrow}) &= \vec{H}_{-S0t}^n(r_{\perp}^{\rightarrow}),\end{aligned}\quad (15)$$

and for TE-type waves:

$$\begin{aligned}\vec{H}_{-S0t}^n(r_{\perp}^{\rightarrow}) &= -\vec{H}_{-S0t}^n(r_{\perp}^{\rightarrow}), \\ \vec{H}_{-S0z}^n(r_{\perp}^{\rightarrow}) &= \vec{H}_{-S0z}^n(r_{\perp}^{\rightarrow}), \\ \vec{E}_{-S0t}^n(r_{\perp}^{\rightarrow}) &= -\vec{E}_{-S0t}^n(r_{\perp}^{\rightarrow}).\end{aligned}\quad (16)$$

Here the index “t” means the transversal component of the vector.

Taking into account Eqs. (8), (15) and (16), we can ascertain the following equations:

$$\frac{d\dot{C}_S^n}{dz} \dot{E}_{zS}^n + \frac{d\dot{C}_{-S}^n}{dz} \dot{E}_{-zS}^n = \frac{1}{N_S^n} \frac{2}{\pi} \int_0^{2\pi} \int_{S_{\perp}} \delta^{\rightarrow} \vec{E}_{S0t}^n dS_{\perp} e^{-jn\omega t} d\omega t \cdot E_{S0z}(\vec{r}_{\perp}),$$

and

$$\operatorname{div} (\dot{C}_S^n \vec{H}_S^n + \dot{C}_{-S}^n \vec{H}_{-S}^n) = \frac{d\dot{C}_S^n}{dz} H_{zS}^n + \frac{d\dot{C}_{-S}^n}{dz} H_{-zS}^n = 0.$$

### 3. Examples of problems with isolation of two-dimensional E-fields

Let us discuss partial cases that illustrate the application of the general theory expounded in Section 1. Such type of microwave electronics problems needs extraction of 2D quasi-static space charge fields.

#### 3.1. Gyroresonance devices

The authors of the works [18] have used equations like Eq. (12) and obtained the solutions for a radial quasi-static space charge field for axially symmetric gyroresonance devices on TE<sub>0i</sub> working types of waves:

$$E_r = -\frac{\tau}{8\pi^2 \varepsilon_0 r} \int_0^{2\pi} [1 + \operatorname{sign}(r - r'(\alpha_0))] d\alpha_0. \quad (17)$$

Here  $\tau = I_0/v_0$  is the linear density of beam charge,  $\varepsilon_0$  is the vacuum permittivity,  $r$  is the radius of the observation point,  $r'$  is the radius of an isophase electron tube,  $\alpha_0$  is the relative phase of rotation of electrons belonging to this tube. The scheme of forming of an isophase tube for TE<sub>01</sub> wave is shown in Fig. 1.

The obtained solution (17) in the works mentioned above allowed defining the main factors of the influence of space charge upon the process of interaction in the gyroresonance devices: acceleration and amplification of electrons phase bunching and the increase of modulation dispersion of electron velocities.

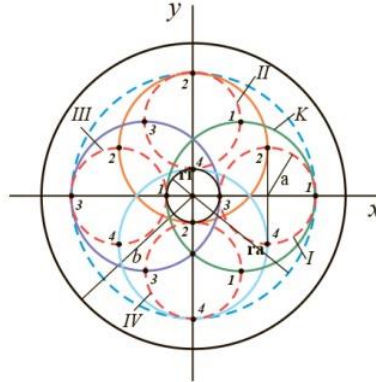


Fig. 2. Four isophase tubes forming  $TE_{11}$  electromagnetic wave in the gyroresonance device. The corresponding isophase tubes are marked with the 'I–IV' symbols.

Рис. 2. Четыре изофазных трубки, образующие в гиросприборе электромагнитные волны  $TE_{11}$ . Соответствующие изофазы трубки обозначены символами «I–IV»

In the Refs. [18] the solution for gyroresonance devices with nonsymmetrical  $TE_{ni}$  working types of waves was obtained similarly. In particular, for  $TE_{11}$ -type waves the isophase tube field has the following form:

$$\dot{E}_t = E_x + jE_y = \frac{\tau}{2\pi\epsilon_0} \left( \frac{1}{2r} [1 + \text{sign}(r - r')] * \left( e^{j\varphi} + \frac{a}{r} e^{2j\varphi} \right) + \frac{3}{2} \frac{a}{b^2} \right). \quad (18)$$

Here  $a$  is the radius of Larmor orbit of electrons on this isophase tube;  $r$ ,  $\varphi$  are the coordinates of the observation point,  $r$  is the isophase tube radius.

The scheme of forming of four isophase tubes for the working  $TE_{11}$  waveguide mode is shown in Fig. 2. Using Eqs. (17) and (18) helped making the comparison of efficiency of the optimized gyro-TWT on  $TE_{01}$  and  $TE_{11}$  modes in the Ref. [18].

### 3.2. Relativistic Cherenkov generators

The radial component of a quasi-static field of the beam plays the significant role in relativistic Cherenkov generators with tubular electron beams and influences upon the movement of the electrons relatively to the working surface



of a corrugated waveguide. This field is considered in [19] as an additional component to  $E_r$  in the following form:

$$E_r^0 = -\frac{\sigma_{0i}}{2r_i b} \left( \frac{1}{\beta_{z0}} - \beta_{z0} \right). \quad (19)$$

Here  $\sigma_{0i} = e|I_{0i}|/\pi\varepsilon_0 m_0 c^3$ ,  $I_{0i}$ , is the current of  $i^{\text{th}}$  layer of the beam,  $r_i$  is the beam radius,  $b$  is the radius of corrugation,  $\beta_{z0} = v_{z0}/c$ ,  $v_{z0}$  is the mean longitudinal velocity of electrons,  $c$  is the light velocity in vacuum,  $e$ ,  $m$  are the electron charge and mass.

## 4. Conclusions

In this paper, the transformation of traditional equations of excitation of a hollow waveguide by an extraneous electric field is made, taking into account the potential electric field in the source area which appears because of the change of a waveguide structure.

## Acknowledgement

The studies connected with the application of the corrected excitation equation for the investigation of gyroresonance devices and relativistic Cherenkov generators have been supported by the Ministry of Education and Science of the Russian Federation (project 3.59.2014/K), the Russian Foundation for Basic Research (grant 15-52-04018) and President's program (Project MK-5426.2015.2).

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## Источники финансирования и выражение признательности

Исследования, связанные с применением скорректированного уравнения возбуждения для исследования гирорезонансных устройств и черенковских релятивистских генераторов, были поддержаны Министерством образования и науки Российской Федерации (проект 3.59.2014/К), Российским фондом фундаментальных исследований (грант 15-52-04018) и программой Президента (проект МК-5426.2015.2).

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