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The electrodynamic modelling of netted linen

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Abstract. In this work, we used the method of volume integral equations (CLI) to build a model of grid structures. The method allows to calculate the reflection and transmission coefficients, the losses in the reticle, taking into account the conductance of the fabric thread and its coating.

1. Model of a cloth from a grid with a square cell

A net-blank of two mutually orthogonal periodic lattices of cylindrical rods is considered, when the lattice period d, the radius of the rod a, the wavelength of the exciting field λ are related by the relation:

$$\lambda >> \ d >> a, \tag{1}$$

under which the task is reduced to a system of one-dimensional integral equations [1]. In this case, the volume of the scattering body is reduced to the aggregate of the volumes of the rods. The electric field in the cross section of each rod is determined by the field external to it, which is the sum of the primary field $\boldsymbol{E}_0$, which excites the network structure as a whole, and the stray field $\boldsymbol{E}_p$, formed by the adjacent elements of the structure. When implementing the method of CLI, the boundary conditions are not used explicitly. Their implementation for the solution obtained using this method was proved in [2]. In the developed model, in addition to condition (1), the longitudinal nature of the current in the grid conductors is taken into account. It can be shown that the contribution of the transverse component of the current is approximately six orders of magnitude smaller than the contribution of the longitudinal one. The interaction of mutually perpendicular grid conductors with an oblique incidence of a plane wave is also taken into account. Exciting plane wave (figure 1) for a lattice rod oriented along the Z axis (conditionally further for short, vertical) and passing through the origin of the coordinates is unambiguously represented by longitudinal components. For the presentation of the fields, cylindrical coordinates are entered separately relative to the vertical axis and the horizontal axis, which is reflected by indices with a radial coordinate ρ:

$$\boldsymbol{E}_{0\mathrm{z}} = \mathbf{z}_0 E_{0z} e^{-ih_z z} J_0(\nu_z \, \rho_z), \tag{2}$$

$$\boldsymbol{H}_{0\mathrm{z}} = \mathbf{z}_0 H_{0z} e^{-ih_z z} J_0(\nu_z \, \rho_z). \tag{3}$$

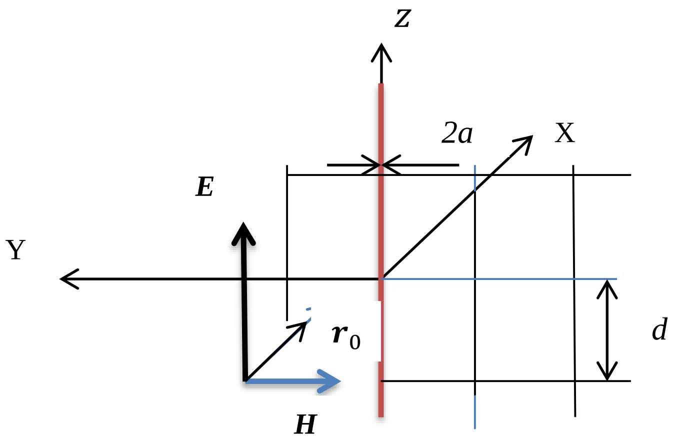

Figure 1. Excitation with a flat wave from conductors of radius *a* and with step *d*.

In a similar form, the exciting field is represented for a rod oriented along the Y axis (horizontal) and also passing through the origin:

$$\boldsymbol{E}_{0y} = \mathbf{y}_0 E_{0y} e^{-ih_y z} J_0(\nu_y\, \rho_y), \tag{4}$$

$$\boldsymbol{H}_{0y} = \mathbf{y}_0 H_{0y} e^{-ih_y z} J_0(\nu_y\, \rho_y). \tag{5}$$

To clarify the introduced notation, we write the representation of the exciting plane wave in the form:

$$\boldsymbol{E_0} = (\boldsymbol{x_0} E_{0x} + \boldsymbol{y_0} E_{0y} + \mathbf{z_0} E_{0z}) e^{-i(h_x x + h_y y + h_z z)}, \tag{6}$$

where $h_{x,y,z} = k_0 cos\theta_{x,y,z}$. ($cos\theta_{x,y,z}$ - cosine guides for the direction of wave propagation). The coefficients $\nu_{x,y,z}$ included in the arguments of the cylindrical functions are also expressed in terms of the direction cosines:

$$\nu_{x,y,z} = \sqrt{k_0^2 - h_{x,y,z}^2} = k_0 sin\theta_{x,y,z}.$$

Effective excitation coefficients E'_{0z},, $H'_{0z}, E'_{0y}, H'_{0y}$' will differ from $E_{0z}, H_{0z}, E_{0y}, H_{0y}$ not only due to the influence of parallel rods, but also because of the influence of orthogonal rods.

The longitudinal components of the internal fields of the rods (for simplicity, homogeneous rods are considered without coating) will have an idea:

$$\boldsymbol{E}_{iy,z} = \boldsymbol{y_0}, \mathbf{z}_0 E_{iy,z} e^{-ih_{y,z} z} J_0(\nu_{iy,z}\, \rho_{y,z}), \tag{7}$$

$$\boldsymbol{H}_{iy,z} = \mathbf{y_0}, \mathbf{z}_0 E_{iy,z} e^{-ih_{y,z} z} J_0(\nu_{iy,z}\, \rho_{y,z}). \tag{8}$$

where $\nu_{iy,z} = \sqrt{k_i^2 - k_0^2 cos\theta_{y,z}}$.

External stray fields are similarly represented:

$$\boldsymbol{E}_{ey,z} = \mathbf{y_0}, \mathbf{z}_0 E_{ey,z} e^{-ih_{y,z} z} H_0^{(2)}(\nu_{y,z}\, \rho_{y,z}) \tag{9}$$

$$\boldsymbol{H}_{ey,z} = \mathbf{y_0}, \mathbf{z}_0 H_{ey,z} e^{-ih_{y,z} z} H_0^{(2)}(\nu_{y,z}\, \rho_{y,z}). \tag{10}$$

The above longitudinal field components uniquely identify all other field components inside and outside the rods:

$$E_{iy,z} = E_{0y,z}T_{ey,z} \tag{11}$$

$$H_{iy,z} = H_{0y,z}T_{hy,z} \tag{12}$$

$$E_{ey,z} = E_{0y,z}S_{ey,z} \tag{13}$$

$$H_{ey,z}=H_{0y,z}S_{hy,z}, \tag{14}$$

where the transmission and reflection coefficients for the electric and magnetic components are:

$$T_{ey,z} = \frac{2}{\pi i \nu_{y,z} a \left(H^{(2)}{}_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\varepsilon_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) H^{(2)}{}_1(\nu_{y,z}a) \right)},$$

$$S_{ey,z} = -\frac{J_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\varepsilon_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) J_1(\nu_{y,z}a)}{\left(H^{(2)}{}_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\varepsilon_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) H^{(2)}{}_1(\nu_{y,z}a) \right)},$$

$$T_{hy,z} = \frac{2}{\pi i \nu_{y,z} a (H^{(2)}{}_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\mu_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) H^{(2)}{}_1(\nu_{y,z}a))},$$

$$S_{hy,z} = -\frac{J_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\mu_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) J_1(\nu_{y,z}a)}{\left(H^{(2)}{}_0(\nu_{y,z}a) J_1(\nu_{iy,z}a) \frac{\mu_{ry,z}\nu_{y,z}}{\nu_{iy,z}} - J_0(\nu_{iy,z}a) H^{(2)}{}_1(\nu_{y,z}a) \right)},$$

where $J_0(\nu_{iy,z}a) J_1(\nu_{iy,z}a)$ – Bessel functions, $H^{(2)}{}_0(\nu_{y,z}a), H^{(2)}{}_1(\nu_{y,z}a)$ – Hankel functions of the second kind.

In contrast to the field $E_{0y,z}, H_{0y,z}$the vertical and horizontal bars of the grid are excited by the resultant (effective) field $E'_{0y,z}, H'_{0y,z}$. Evaluation of the additional contribution to the effective exciting field of a horizontal rod of vertical rods gives the following result:

$$E'_{0y\perp} = \frac{2}{\nu_z^2}\left\{\frac{h_z h_y}{dh_x} E'_{0z} S_{ez} + \frac{\omega\mu_0}{d} H'_{0z} S_{hz} sign(x)\right\} e^{-ih_x|x|} \quad , \tag{15}$$

$$H'_{0y\perp} = \frac{2}{\nu_z^2}\left\{\frac{h_z h_y}{dh_x} H'_{0z} S_{hz} - \frac{\omega\varepsilon_0}{d} E'_{0z} S_{hz} sign(x)\right\} e^{-ih_x|x|} \tag{16}$$

For an additional effective exciting field in vertical rods with horizontal rods, the similar relations take place:

$$E'_{0z\perp} = \frac{2}{\nu_y^2}\left\{\frac{h_z h_y}{dh_x} E'_{0y} S_{ey} - \frac{\omega\mu_0}{d} H'_{0y} S_{hy} sign(x)\right\} e^{-ih_x|x|} \tag{17}$$

$$H'_{0z\perp} = \frac{2}{\nu_y^2}\left\{\frac{h_z h_y}{dh_x} H'_{0y} S_{hy} + \frac{\omega\varepsilon_0}{d} E'_{0y} S_{hy} sign(x)\right\} e^{-ih_x|x|} \tag{18}$$

The function $sign(x)$ implies $sign(0) = 0$.

Taking into account the above relations, we can write down systems of equations for finding the resulting fields $E'_{0z}, H'_{0z}, E'_{0y}, H'_{0y}$:

$$E'_{0y}\left(1 - 2S_{ey}\sum_{n=1}^{\infty} H_0^{(2)}(\nu_y \rho_{yn}) \cos(h_z nd)\right) - \frac{2}{\nu_z^2}\left\{\frac{h_z h_y}{dh_x} E'_{0z} S_{ez}\right\} = E_{0y}, \tag{19}$$

$$-\frac{2}{\nu_y^2}\left\{\frac{h_z h_y}{dh_x} E'_{0y} S_{ey}\right\} + E'_{0z}\left(1 - 2S_{ez}\sum_{n=1}^{\infty} H_0^{(2)}(\nu_z \rho_{zn}) \cos(h_y nd)\right) = E_{0z}, \tag{20}$$

$$H'_{0y}\left(1-2S_{hy}\sum_{n=1}^{\infty}H_0^{(2)}\left(\nu_y\rho_{yn}\right)\cos(h_z nd)\right)-\frac{2}{\nu_z^2}\left\{\frac{h_z h_y}{dh_x}H'_{0z}S_{hz}\right\}=H_{0y}, \quad (21)$$

$$-\frac{2}{\nu_y^2}\left\{\frac{h_z h_y}{dh_x}H'_{0y}S_{hy}\right\}+H'_{0z}\left(1-2S_{hz}\sum_{n=1}^{\infty}H_0^{(2)}\left(\nu_z\rho_{zn}\right)\cos(h_y nd)\right)=H_{0z}, \quad (22)$$

The system (19), (20) with respect to the electric field and the system (21), (22) with respect to the magnetic field are solved separately. According to the found values of $E'_{0z}, H'_{0z}, E'_{0y}, H'_{0y}$ the electric field dissipated by the lattice is determined by the relations:

$$E_{sy}=\left\{\frac{2E'_{0y}S_{ey}}{dh_x}+\frac{2}{\nu_z^2}\left\{\frac{h_z h_y}{dh_x}E'_{0z}S_{ez}+\frac{\omega\mu_0}{d}H'_{0z}S_{hz}sign(x)\right\}\right\}e^{-ih_x|x|-ih_y y-ih_z z}, \quad (23)$$

$$E_{sz}=\left\{\frac{2E'_{0z}S_{ez}}{dh_x}+\frac{2}{\nu_y^2}\left\{\frac{h_z h_y}{dh_x}E'_{0y}S_{ey}-\frac{\omega\mu_0}{d}H'_{0y}S_{hy}sign(x)\right\}\right\}e^{-ih_x|x|-ih_y y-ih_z z}, \quad (24)$$

$$E_{sx}=-\left\{\frac{E_{sy}h_y+E_{sz}h_z}{h_x}\right\}e^{-ih_x|x|-ih_y y-ih_z z}. \quad (25)$$

The properties of the threads when calculating the external field are taken into account by the coefficients $S_{ey}, S_{ez}, S_{hz}, S_{hy}$. The coefficients $T_{ey,z}, T_{hy,z}$ determine the field inside the rods and make it possible to calculate the absorbed net-weighted power. When analyzing a web of coated conductors, the expressions for these coefficients become more complicated, but the calculated relations (15) - (25) are preserved.

2. Simulation results

The calculations carried out using the MATHCAD software demonstrate the adequacy of the model when studying the characteristics of the web with regard to the coating or oxide film of conductors with a relative error not exceeding 0.5% of the boundary conditions and energy balance conditions.

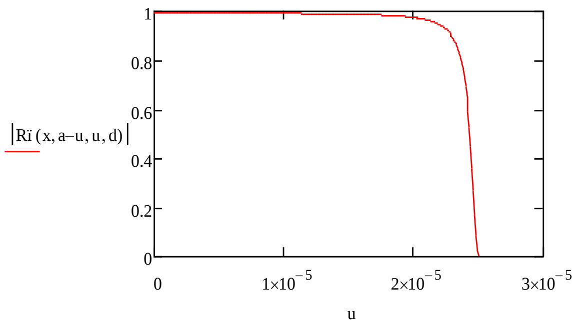

Figure 2. Mesh transfer ratio as a function of the thickness of the oxide layer.

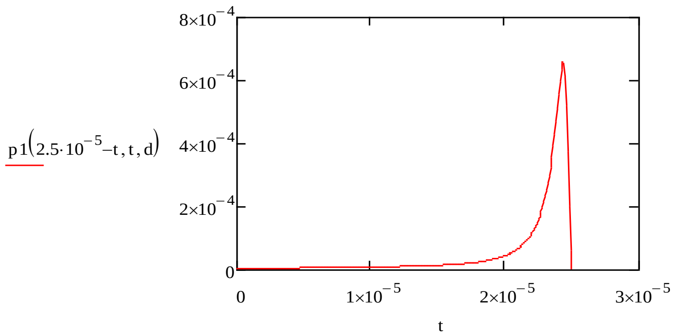

Figure 3. The density of power absorbed by the web as a function of oxide film thickness.

With the help of the developed model, the correctness of the application of experimental methods and applied packages for studying the characteristics of the web by waveguide methods is confirmed. Of considerable interest is the study of webs of twisted threads [3]. In this regard, a model of a cloth

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with braided threads in the form of a bundle of cylindrical conductors was developed, allowing to evaluate the degree of influence of geometry elements on the characteristics of the canvas (figure 4) for a thread with 6 conductors.

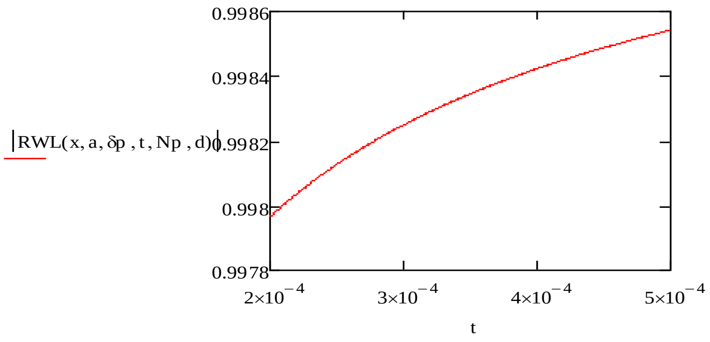

Figure 4. Reflection coefficient webs as a function of weaving radius (Np = 6).

3. Conclusion
The developed netted linen model allows analyzing its electrodynamic characteristics. It is interesting to further investigate the thermal characteristics taking into account the identified features of heat release (figure 3)

References
[1] Dautov O Sh 1990 *Calculation of the electromagnetic field of a given distribution of volume currents Automated Design of Microwave Devices* (Moscow: MIREA) pp 4-16

[2] Dautov O Sh 1991 Equivalence of integral and integro-functional equations of electrodynamic diffraction problems on inhomogeneous bodies *Izv. universities Radiofizika* **34(8)** 936-46

[3] Belyaev O F, Zavaruev Z V and Khalimanovich V I 2016 The change in the nature of the dependence of the reflection coefficient of electromagnetic waves by metal trictates under the influence of contact resistances *Materials NTK INNOVATIONS* 21-4