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ANALYSIS OF ARBITRARY PROPAGATION OF ELECTROMAGNETIC WAVES THROUGH THE POLARIZATION-SELECTIVE SURFACE

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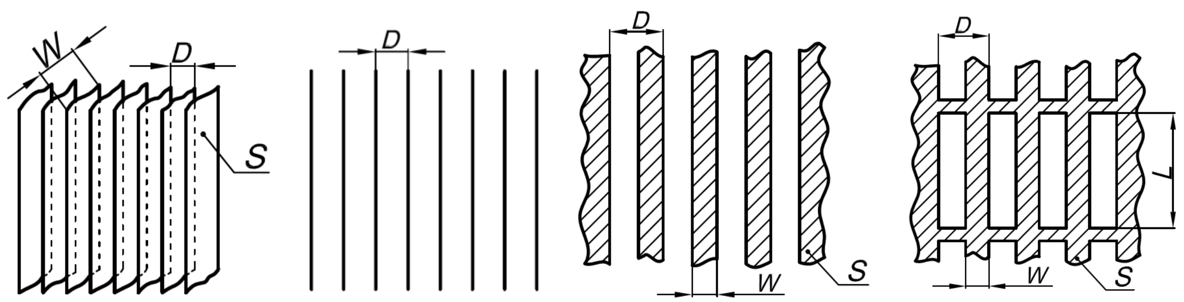
Abstrakt. *The determination of transmission and reflection of wave propagating at arbitrary angle between the polarization axis of polarization filter and polarization axis of the wave is hardly covered in literature. The general case of the propagation of electromagnetic wave through the polarization-selective surface at random angle is considered. The decomposition strategy, applied to general oriented electromagnetic field incident onto the polarization-selective surface, allows to bring the problem of the determination of the transmission and reflection coefficients to examination of the individual E-case and H-case of parallel and perpendicular wave polarization. The results of the calculated relation of the propagation coefficient through a spiral polarization-selective cylindrical structure irradiated with a linear source, located parallel to the axis of the structure, for two orthogonal polarizations of the wave for the maximum transmission and maximum reflection cases are presented.*

Keywords: polarization-selective structure, vector decomposition, electromagnetic field, transmission coefficient.

Introduction. Metal grids of parallel round-shaped or planar wires are widely used in radio engineering as passive antenna reflectors instead of solid metal shields. This allows us to save the costs of material, to reduce weight and wind load. Another application of such elements is to use them as polarization filters (PF), which enables to provide selective transmission of electromagnetic waves (EMW) depending on their polarization characteristics. The most common types of PF are the following structure formed of plane-parallel wafers (fig. 1, *a*), thin round-shaped conductors (fig.1, *b*), thin strips on a dielectric base or without it (fig.1, *c*), slot-perforated metal plane (fig.1, *d*), etc. The main geometrical features, which characterize the mentioned structure are the grid spacing *D*, the strips width *W* and their thickness *S*. The main electrodynamic characteristics of the structures are the wave transmission ratio (K_{tr}) and reflection ratio (K_{refl}) from the grid depend on the incidence angle and polarization of the wave.



a *b* *c* *d*

Fig. 1. The main types of polarization filters

In order to solve the problem it is required to determine the values of K_{tr} and K_{refl} of electromagnetic waves from the metal grid of the polarization filter as a part of the apparatus for loose materials microwave treatment. It consists of concentric surfaces and cavities. The internal cylindrical volume provides continuous material feeding and processing. Over the first chamber the polarization filter is formed, function of which is to pass the electromagnetic waves with corresponding polarization. Moreover, it can be designed as a spiral-wound wire or as a perforated sheet cylinder, so that the polarization axis of the surface at the opposite sides of the cylinder is oriented in opposite directions (turned in 90^o). The internal volume is irradiated by electromagnetic waves of industrial frequency (2,45 GHz) with the irradiator, e.g. a slotted waveguide. The matching surface is a part of the device, and designed for compensation of the reflected waves from the processing material. It is designed as coaxial with the central zone of the inner chamber. The matching function can be realized either with insertion of dielectric tube or by the metal grid surface at the required amplitude and phase conditions for the reflected wave. To provide the conditions and to determine the total field strength distribution in the processing section, the determination of the wave transmission and wave reflection from the polarization surface is required depending on the incident wave angle with arbitrary orientation of the polarization angle towards the polarization axis of PF.

Let us make the assumption that the research doesn't consider the obtaining of expressions for dependence of EMW transmission and reflection from the different polarization-selective structures, since such expressions are represented in [1 – 4].

The determination of transmission and reflection of wave propagating at any angle between the polarization axis of PF and polarization axis of the wave is hardly covered in literature.
We consider that in order to study the structure the K_{refl} and K_{tr} dependency on incidence angle for parallel and perpendicular polarization for specific *E*-case and *H*-cases is known.

Main part. Let us restrict the consideration of EMW incidence onto the polarizing filter to the separate *E*-case and *H*-case for wave with parallel (index «||») and perpendicular (index «$\perp$») polarizations to simplify the determination of microwave energy transmission through the surface. In this manner each of the vectors of the incident electromagnetic wave should be decomposed into the following components: $\overline{E}_{\|E}$, $\overline{E}_{\perp E}$, $\overline{E}_{\|H}$, $\overline{E}_{\perp H}$ and $\overline{H}_{\|E}$, $\overline{H}_{\perp E}$, $\overline{H}_{\|H}$, $\overline{H}_{\perp H}$. We will understand *perpendicular polarization* as such the orientation of the electromagnetic field vector relative to orientation of polarization-filter axis where the vector $\overline{E}$ is perpendicular to the polarization axis of PF; *parallel polarization* – the case in which the vector $\overline{H}$ is perpendicular to the axis of polarization. The *E*-case is considered as a case of wave incidence on the surface while the electric field vector is parallel to the incidence plane, *H*-case – a case when the vector of the magnetic field is parallel to the incidence plane (fig. 2, *a*).

Let us introduce vectors $\overline{i}$, $\overline{j}$ with the origin at incidence point of the wave on the surface, such that $\overline{i}$ belongs to the incidence plane and is perpendicular to the wave propagation direction; $\overline{j}$ belongs to the surface of PF (or tangential to it) and is perpendicular to the incidence plane (fig. 2, *a*). Let angle between vectors $\overline{i}$ and $\overline{E}$ be denoted by α, the angle between the incidence plane and polarization axis sites by β, and the angle between the direction of the wave propagation and normal to surface of PF sites by θ.

So we then decompose the incident wave vectors on the *E*-case and *H*-case components, which can be determined by projecting of corresponding initial vectors onto the unit vectors $\overline{i}$, $\overline{j}$:

$$\begin{aligned} \overline{E}_E &= \overline{i}\left|\overline{E}\right| \cdot \cos(\alpha), \\ \overline{E}_H &= \overline{j}\left|\overline{E}\right| \cdot \sin(\alpha). \end{aligned} \tag{1}$$

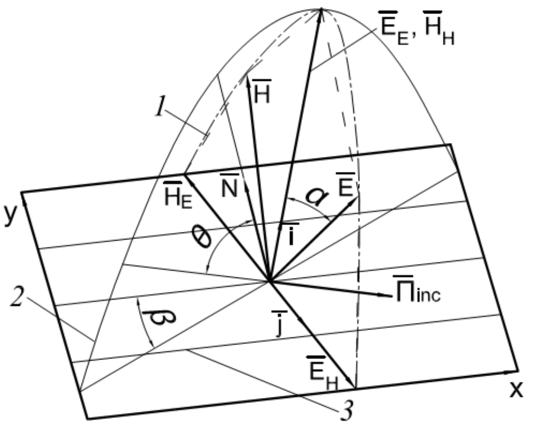
Wave front corresponding to vector $\overline{E}_E$ coincides with the initial wave front, and magnetic vector of the wave lies in the plane of the grid; wave front, corresponding to $\overline{E}_H$ coincides with the primary wave front and its electric vector lies in the plane of the grid.

We then consider two pairs of vectors separately and perform the decomposition of each into parallel and perpendicular polarization components.

Let us introduce vectors $\overline{m}$ and $\overline{n}$ with the origin at the wave incidence point such that the both coincide with PF surface, $\overline{m}$ coincides with polarization axis of PF and $\overline{n}$ is perpendicular to it (fig. 2, *b*). Then we consider the separate components of the vector $\overline{E}_H$, so $\overline{E}_{H\parallel}$ is the projection of $\overline{E}_H$ on the vector $\overline{m}$ and accordingly $\overline{E}_{H\perp}$ – projection on the vector $\overline{n}$.

$$\overline{E}_{H\perp} = \overline{n}\left|\overline{E}_H\right|\cos(\beta),$$
$$\overline{E}_{H\parallel} = \overline{m}\left|\overline{E}_H\right|\sin(\beta). \qquad (2)$$

We consider vector $\overline{E}_E$ as the pair of vectors $\overline{E}_{E\parallel}$ and $\overline{E}_{E\perp}$, hence $\overline{E}_{E\parallel} + \overline{E}_{E\perp} = \overline{E}_E$. It is obviously, that the initial and two derivative vectors must lie in the same plane. Therefore, it is sufficient to build a single plane through the vector $\overline{i}$, on which we introduce two vectors $\overline{i}_\perp$ and $\overline{i}_\parallel$, such that $\overline{i} = \overline{i}_\perp + \overline{i}_\parallel$. Hence $\overline{E}_{E\parallel}$ lies on $\overline{i}_\parallel$ and $\overline{E}_{E\perp}$ lies on $\overline{i}_\perp$. To simplify computation let us construct the surface in the manner of coincidence with $\overline{n}$. So $\overline{i}_\parallel$ is the projection of $\overline{i}$ on a surface which include vector $\overline{m}$ and is perpendicular to the surface of PF, $\overline{i}_\perp$ – projection of $\overline{i}$ on $\overline{n}$. Let us denote the constructed surface by *N*.



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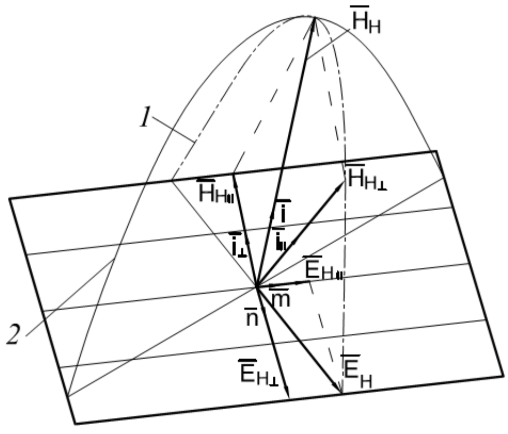

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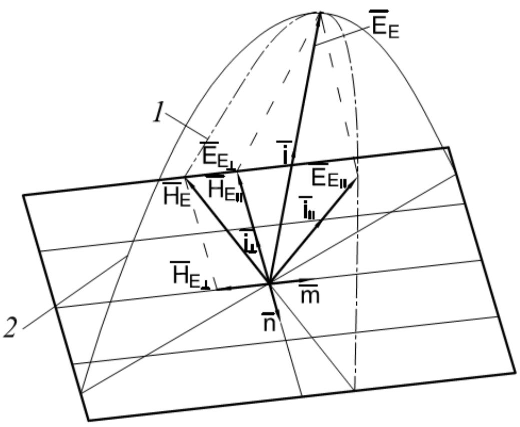


c

Fig. 2. Vector decomposition on polarization surface: *1* – incidence wave front; *2* – incidence plane; *3* – polarization axis of polarization filter

The angle between the vectors $\overline{i}$ and $\overline{n}$ can be found from the cosine theorem for trihedral angle:

$$\cos(\widehat{\overline{i},\overline{n}}) = \cos(\theta)\cos(\beta') + \sin(\theta)\sin(\beta')\cos(A), \qquad (3)$$

where β'=90°-β denotes the angle between $\overline{n}$ and projection of $\overline{i}$ on the surface of PF. Angle *A* is the angle between the planar angles θ and β, and is equal to 90°. Performing trigonometric transformation we can rewrite (3) as:

$$\cos(\widehat{\overline{i},\overline{n}}) = \cos(\theta)\sin(\beta)\,. \qquad (4)$$

Hence we can find the expressions:

$$\overline{E}_{E\perp} = \overline{i}_\perp\left|\overline{E}_E\right|\cos(\widehat{\overline{i},\overline{n}}). \qquad (5)$$

Performing the analogous conversion we get:

$$\overline{E}_{E\parallel} = \overline{i}_\parallel\left|\overline{E}_E\right|\cos(90^o - \widehat{\overline{i},\overline{n}}) = \overline{i}_\parallel\left|\overline{E}_E\right|\sin(\widehat{\overline{i},\overline{n}}). \qquad (6)$$

The angle between the vectors $\overline{i}_\parallel$ and $\overline{m}$ corresponds to the angle of incidence of the wave component of *H*-case for perpendicular polarization and is equal to angle of incidence of the wave of *E*-case for parallel polarization. The components of the initial wave, defined by pair of the vectors $\overline{E}_{H\|}$ and $\overline{E}_{E\perp}$ are oriented normally to the plane of PF.

According to above the total wave transmission ratio is given by:

$$K_{tr}(\alpha) = \frac{\left|\overline{E}_{tr}\right|}{\left|\overline{E}_{inc}\right|}, \qquad (7)$$

where electric vector of the incident wave can be presented as

$$\overline{E}_{inc} = \overline{E}_{E\perp} + \overline{E}_{E\|} + \overline{E}_{H\perp} + \overline{E}_{H\|}, \qquad (8)$$

and similarly, the electric vector of the transmitted wave can be presented as

$$\overline{E}_{tr} = \overline{E}_{E\perp tr} + \overline{E}_{E\| tr} + \overline{E}_{H\perp tr} + \overline{E}_{H\| tr}, \qquad (9)$$

where $\overline{E}_{E\perp tr} = \overline{E}_{E\perp} K(\alpha_{E\perp})_{tr_{E\perp}}$, $\overline{E}_{E\| tr} = \overline{E}_{E\|} K(\alpha_{E\|})_{tr_{E\|}}$, $\overline{E}_{H\perp tr} = \overline{E}_{H\perp} K(\alpha_{H\perp})_{tr_{H\perp}}$, $\overline{E}_{H\| tr} = \overline{E}_{H\|} K(\alpha_{H\|})_{tr_{H\|}}$, – wave transmission ratio of corresponding component of the initial wave depending on the angle of incidence α.

The angles of incidence for each wave component are equal to:

$$\alpha_{E\|} = \alpha_{H\perp},\ \alpha_{H\perp} = \widehat{\overline{m}, \overline{i}_{\|}} = \arccos\left(\cos(\theta')\sin(\beta)\right) = \arccos\left(\sin(\theta)\sin(\beta)\right),\ \alpha_{E\perp} = \alpha_{H\|},\ \alpha_{H\|} = 0.$$

Apparently, two constituent waves, namely components of *E*-case of parallel and *H*-case of perpendicular polarization, are characterized by the same incidence angle; others two components do not depend on the angle of incidence of the initial wave and correspond to the case of normal incidence for the *E*-case of perpendicular and *H*-case of parallel polarization onto the polarization-selective surface.

Calculation results. The test calculation of transmission ratio of electromagnetic waves through the polarization-selective structure has been performed according to fig. 2, irradiated with a linear microwave source. The diagram of the installation is shown in fig. 3, where *1* – microwave energy source, *2* – cylindrical polarization-selective structure. Calculation is carried out depending on the radiation angle Ψ in the plane perpendicular to the axis of the structure *2*. We consider the polarizing filter designed as a spiral wound of thin round-shaped wire with winding angle 45° to the axis of the cylinder. The angle between the polarization axis of the incident wave and the cross-sectional plane of the structure (perpendicular to the axis) is -45°. Thus, while the wave incidents inside of the cylinder the maximum transmission of MW is observed, on the other hand, while it incidents from without the maximum reflection occurred. The diameter of the helix wire in studied model is 1 mm, the distance from the phase center of the radiator to the axis of the structure is 400 mm, diameter of helix – 200 mm, which corresponds to the maximum value of the angle Ψ equal to 12,5°, exceeding which the wave does not reach the surface of PF. The frequency on which the modeling has performed is 2,45 GHz. Transmission dependence of the wave through the polarization-selective structure of thin wires for specific cases is taken from [1].

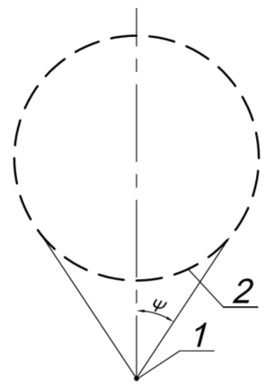
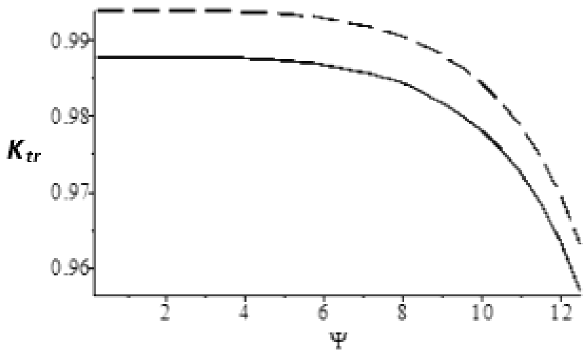


Fig. 3. Sketch of installation: *1* – phase center of source; *2* – polarization filter

The relation between the transmission ratio into the structure and the value of angle Ψ, obtained according to (7) for maximum transmission is shown in fig. 4, *a*. Corresponding case for the maximum reflection is shown in fig. 4, *b*. The solid curves correspond to the distance between the conductors in the coils equal to 5 mm, dotted – 10 mm.

Looking the calculated curves one can notes that increasing of radiation angle Ψ will reduce the beneficial effects of PF. It is obvious that with increasing of Ψ the value of the angle of incidence of the waves also increases, which on the one hand, causes an increase of reflection, and on the other hand causes mismatch between the incident wave polarization and polarization axis of PF. As the consequence of the mentioned effect, the polarization of transmitted and incident waves in general will not be the same.



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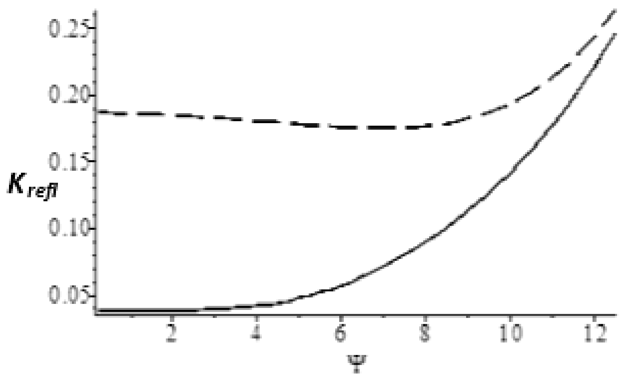

b

Fig. 4. Relation of the transmission coefficient into the structure

Conclusions. The decomposition strategy, applied to general oriented electromagnetic field incident onto the polarization-selective surface, allows us to bring the problem of the determination of the transmission and reflection coefficients to examination of the individual *E*-case and *H*-case of parallel and perpendicular wave polarization. Let us stress the fact that two of the four decomposed components correspond to normal incidence of wave onto the surface and do not depend on the angle of incidence of the initial wave, the other two components are characterized with identical angle.

The test results of the considered computations show that the wave transmission ratio through the cylindrical polarization-selective structure of spiral wound thin conductors depends on the radiation angle, moreover the polarization of transmitted wave through the grid, in general, differs from the incident one as a result of different conditions of both polarization components on the polarizing surface.

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Аналіз довільного проходження електромагнітних хвиль крізь поляризаційно-вибіркову поверхню

Розглянуто загальний випадок падіння електромагнітної хвилі на поляризаційно-вибіркову поверхню під довільним кутом, запропоновано спосіб визначення коефіцієнтів проходження та відбивання хвилі від такої структури шляхом розкладання векторів напруженості електричного та магнітного полів на окремі характерні складові. Приведено результати розрахунку залежності коефіцієнта проходження крізь спіральну циліндричну поляризаційно-вибіркову структуру при опроміненні лінійним джерелом, розташованим паралельно до осі структури, для двох взаємно ортогональних поляризацій хвилі для випадку максимального проходження та максимального відбивання.

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Анализ произвольного прохождения электромагнитных волн через поляризационно-избирательную поверхность

Рассмотрен общий случай падения электромагнитной волны на поляризационно-избирательную поверхность под произвольным углом, предложен способ определения коэффициентов прохождения и отражения волны от такой структуры путем разложения векторов напряженности электрического и магнитного полей на отдельные характерные составляющие. Приведены результаты расчета зависимости коэффициента прохождения через спиральную цилиндрическую поляризационно-избирательную структуру при облучении линейным источником, расположенном параллельно оси структуры, для двух взаимно ортогональных поляризаций волны для случая максимального прохождения и максимального отражения.