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ELECTRODYNAMICS AND WAVE PROPAGATION

Experimental Study of the Field Structure of the Surface Electromagnetic Wave in an Anisotropically Conducting Tape

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Abstract—It is shown that, in the frequency band 3–5.2 GHz, a tape of metal conductors supports slow waves. The field structure of the surface wave in an anisotropically conducting tape is studied experimentally. It is found that the electromagnetic field of the tape has three electric and two magnetic components. Intensity distributions of all field components, the slowing factor of the surface wave, and the loss per unit length are measured.

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INTRODUCTION

Slow waves in guiding structures may be of interest in applications where it is required, for example, to obtain rather intense longitudinal electric fields. Below, it will be shown that a tape with conductance along a chosen direction (below, an anisotropically conducting band) satisfies this requirement: it supports propagation of surface waves in a wide frequency band, has low loss, and is rather elastic.

1. FORMULATION OF THE PROBLEM

A planar slowing structure formed by a tape with an arbitrary fixed direction of anisotropic conductance was first proposed and analyzed in [1]. In this paper, an integral equation for eigencurrents was derived and solved rigorously with the help of a numerical method; for the case narrow tapes, an analytical solution was obtained. The geometry of such a slowing structure is shown in Fig. 1. The tape of width $2a$ is formed from copper conductors of diameter d, which are placed with period p. Let us analyze the structure of the field in a tape with the direction of conductance making the angle $\Psi = 90°$ with axis z.

All components of the electromagnetic field of the fundamental mode of the surface wave can be expressed in terms of one real function $U(x, y)$ [1]. This function has the meaning of the transverse distribution of component Π_y of the Hertz vector. Function $U(x, y)$ is even along coordinate x and is continuous across the tape (at $x = 0$, $|y| < a$); its partial derivative $\partial U/\partial x$ is discontinuous on the tape. For the fundamental mode, this function is also even along coordinate y:

$$U(x,-y) = U(x,y). \tag{1}$$

In this case, the electric field has the following components:

$$E_x = \frac{1}{k^2}\frac{\partial U(x,y)}{\partial x \partial y}\exp(-ihz) \tag{2}$$

(an odd function of y),

$$E_y = \left(1 + \frac{1}{k^2}\frac{\partial^2}{\partial y^2}\right)U(x,y)\exp(-ihz) \tag{3}$$

(an even function of y),

$$E_z = \frac{-ih}{k^2}\frac{\partial U(x,y)}{\partial y}\exp(-ihz) \tag{4}$$

(an odd function of y),

where $k = 2\pi/\lambda$ is the propagation constant in free space, $h = 2\pi/\Lambda$ is the propagation constant of the surface wave, λ is the wavelength in vacuum, and Λ is the wavelength of the surface wave.

The magnetic field has the following components:

$$H_x = \frac{-h}{k}U(x,y)\exp(-ihz) \text{ (an even function of } y\text{)}, \tag{5}$$

$$H_y = 0, \tag{6}$$

$$H_z = \frac{i}{k}\frac{\partial U(x,y)}{\partial x}\exp(-ihz) \text{ (an even function of } y\text{)}. \tag{7}$$

It follows from expressions (5)–(7) and evenness property (1) that, in half-spaces $x < 0$ and $x > 0$, the magnetic-field vector has elliptical polarization with opposite signs of rotation. In the domain ($x = 0$, $|y| > a$), the magnetic field is linearly polarized and is directed along the x axis. As was noted in [2], the fundamental

† Deceased.

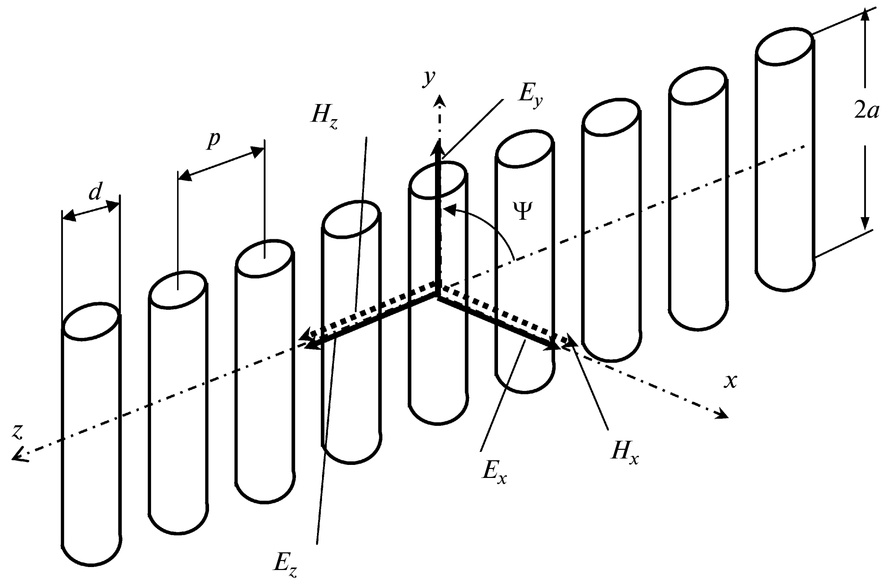

Fig. 1. Geometry of the anisotropically conducting surface-wave line.

mode of an anisotropically conducting tape exists at arbitrarily low frequencies.

Orientation of field components (5)–(7) in the coordinate system of the tape is shown in Fig. 1.

Let us consider the technique of performed studies and the results of these studies.

2. SLOWING FACTOR OF THE SURFACE WAVE IN THE ANISOTROPIC TAPE AND THE LOSS PER UNIT LENGTH

Slow waves can propagate along an anisotropically conducting tape. For these waves, propagation constant h is larger than wave number k; in this case, the slowing factor of the surface wave is described by the ratio

$$\gamma = h/k \equiv \lambda/\Lambda. \tag{8}$$

For experimental studies, two tapes with anisotropic conductance were manufactured. One tape was made of a special material with conductors having the diameter $d = 0.12$ mm. The conductors were placed between Dacron and polyethylene layers with the period $p \approx 0.25$ mm. The other tape was made of conductors with the diameter $d = 0.7$ mm, which were sealed between polyethylene layers with the period $p \approx$ 2.5 mm. The width of both tapes $2a \simeq 28$ mm and the length of each tape is about 1 m. The dependence of slowing factor γ on frequency $f = c/\lambda$ (where c is the velocity of light in vacuum) was studied with the use of the layout shown in Fig. 2. The data obtained with both tape specimens were found to be rather close; therefore, below, we discuss the results obtained for the first specimen. Tape *1* is excited by component E of the field of the fundamental mode of rectangular waveguide *2*; the tape plane is parallel to the narrow wall of the waveguide. Forward surface wave *3* propagates along the tape from the waveguide end to reflector *4* and reflected wave *5* propagates in the opposite direction. Thus, standing-wave conditions are implemented in the tape. Short Γ-shaped oscillator *6* is excited by component E_z of the tape eigenmode. The signal from the output of this oscillator enters microwave detector *7* and, afterwards, is recorded by oscilloscope *8*. Moving the oscillator along the z axis, it is possible to determine the distance between adjacent minima of the standing wave $l_{\min}$, which, as is well known, is $\Lambda/2$.

The studies results are presented in Fig. 3, where values of $\gamma - 1$ are plotted along the vertical axis, values of ka are plotted along the horizontal axis, and corresponding frequencies $f = kc/2\pi$ are plotted along the upper horizontal axis. The figure contains also experimental points obtained from rigorous calculation [1] and calculation data obtained in the approximation of small values of parameter ka. These data were obtained on the basis of Eq. (23) from [1], which is valid at small ka and $\Psi = \pi/2$:

$$J_0(ka) + kaJ_1(ka)\ln\left(\frac{\gamma ka}{4}\sqrt{\frac{h^2}{k^2} - 1}\right) = 0. \tag{9}$$

The solution of this equation for h/k is

$$\frac{h}{k} \equiv \gamma = \sqrt{1 + \frac{16}{(\chi ka)^2}\exp\left[-\frac{2J_0(ka)}{kaJ_1(ka)}\right]}, \tag{10}$$

where $J_n(ka)$ is the Bessel function of the first kind of order n and $\chi \cong 1.78$ is the Euler constant. As seen

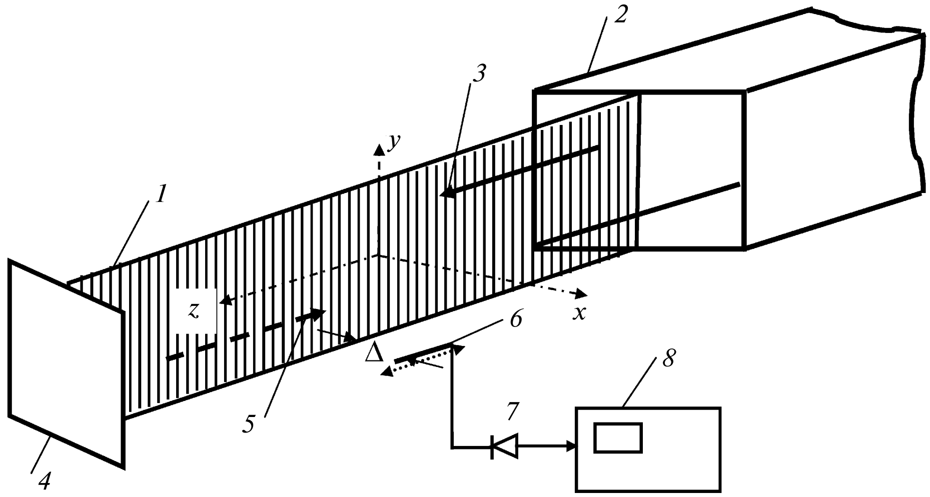

Fig. 2. Layout for implementation of standing-wave operating conditions: (*1*) anisotropically conducting tape, (*2*) rectangular waveguide, (*3*) forward wave, (*4*) end reflector, (*5*) reflected wave, (*6*) Γ-shaped probe, (*7*) detector, and (*8*) recorder.

from the figure, experimental and numerical results are in good agreement.

Let us estimate loss q in the studied surface-wave line from the obtained experimental data. Using the ratio of measured field intensities at the maximum and the minimum of the standing wave, $\nu = \frac{I_{\min}}{I_{\max}} = 0.014$, we obtain that, for a length of measured tape section of ~1 m, $q \simeq 2$ dB/m.

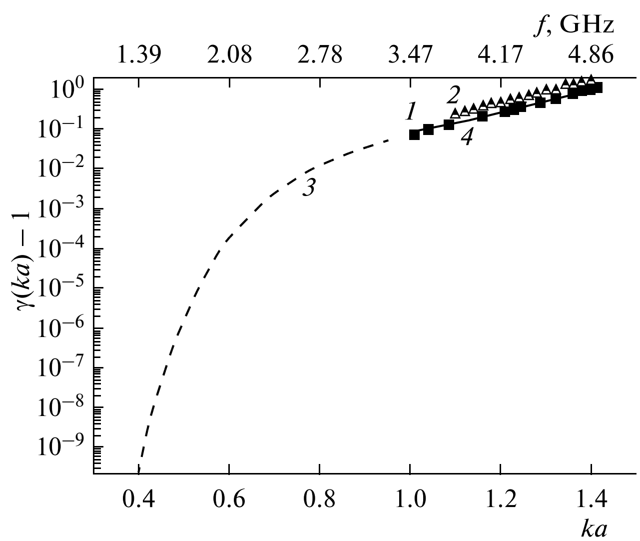

Fig. 3. Slowing factor of the surface wave as a function of ka: (*1*) experiment, (*2*) rigorous calculation, (*3*) approximate calculation for small ka, and (*4*) envelope of experimental values.

3. ANALYSIS OF INTENSITY DISTRIBUTIONS OF ELECTRIC COMPONENTS OF THE FIELD OF THE SURFACE WAVE

The layout for measuring the intensity distributions of electric-field components in tape *1* is shown in Fig. 4. Sensors of the field of propagating wave *2* are short wire probes *3*, *4*, and *5* placed parallel to corresponding field components. Minimum distance Δ between the probes and the tape plane is ~2–6 mm. Electric signals from the probes pass through microwave detector *6* and enter recorder *7*. Intensity distributions along coordinates x and y of three electric-field components, $E_x(x)$; $E_y(x)$; $E_z(x)$; $E_x(y)$; $E_y(y)$, and $E_z(y)$, were studied.

The measurement results are shown in Figs. 5 and 6. As seen from Fig. 5, intensities of all field components decrease more than fivefold as the distance to the tape surface becomes 20 mm (0.4Λ, see the upper horizontal axis) along the x axis, and the greatest rate of decrease corresponds to component E_x. Vertical lines in Fig. 6 at $y = \pm 14$ mm mark positions of the tape edges. As seen, the field of component E_y is most localized, and intensities of all components decrease more than tenfold at a distance of 25 mm from the tape center. Note that the behavior of distributions in Fig. 6 corresponds to expressions (2)–(4); i.e., components E_x and E_z are described by odd functions and component E_y is describe by an even function.

4. ANALYSIS OF INTENSITY DISTRIBUTIONS OF ELECTRIC COMPONENTS OF THE FIELD OF THE SURFACE WAVE

The layout for measuring the intensity distributions of magnetic-field components in the tape is shown in

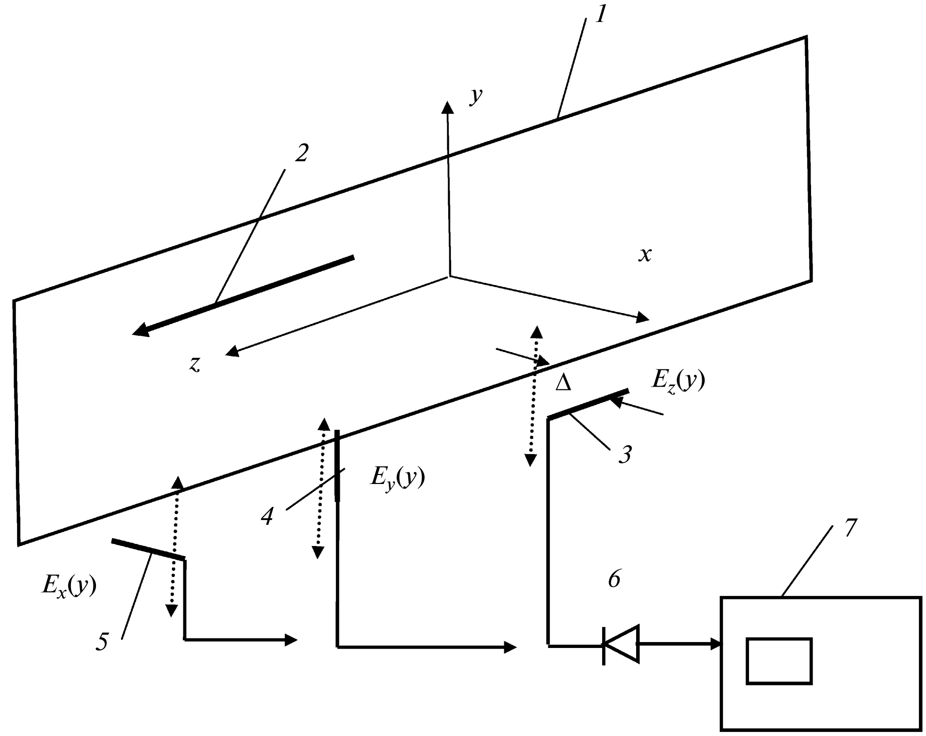

Fig. 4. Layout for measuring the intensity distributions of electric components of the field of the surface wave: (*1*) plane of the anisotropically conducting tape; (*2*) forward wave; (*3*, *4*, and *5*) sensors of field components E_z, E_y, and E_x, respectively; (*6*) detector; and (*7*) recorder.

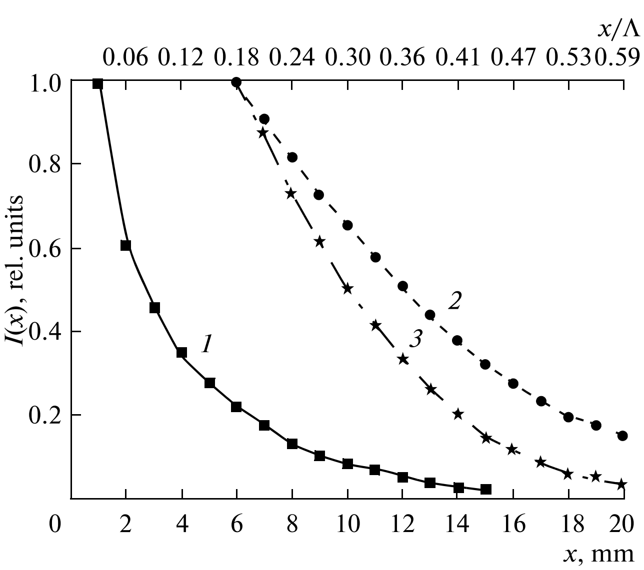

Fig. 5. Intensity distributions $I_e(x)$ of electric components of the filed of the surface wave as functions of transverse coordinate x: (*1*) $|E_x(x)|^2$, (*2*) $|E_y(x)|^2$, and (*3*) $|E_z(x)|^2$.

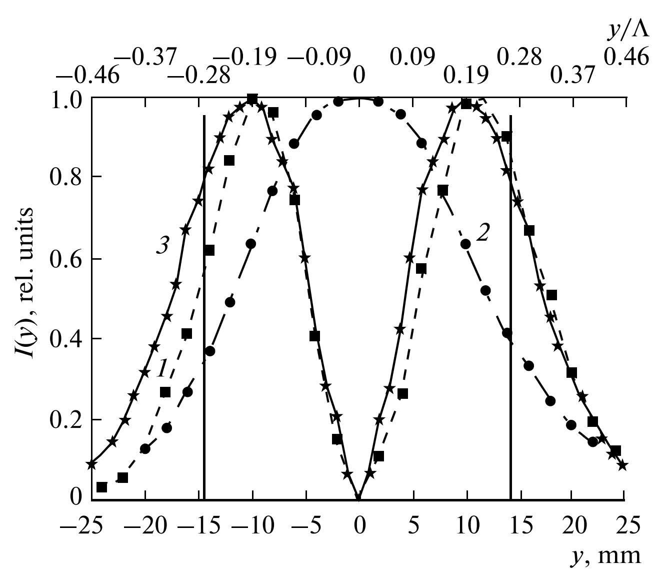

Fig. 6. Intensity distributions $I_e(y)$ of electric components of the filed of the surface wave as functions of transverse coordinate y: (*1*) $|E_x(y)|^2$, (*2*) $|E_y(y)|^2$, and (*3*) $|E_z(y)|^2$.

Fig. 7. As in Fig. 2, tape *1* supports surface wave *2*, which propagates along the z axis. In order to ensure traveling-wave conditions, matched load *3* is placed at the tape end. Component E_z of the surface wave excites Γ-shaped probe *4* of the output receiver. Probe *4* is placed near the maximum of distribution E_z (Fig. 6).

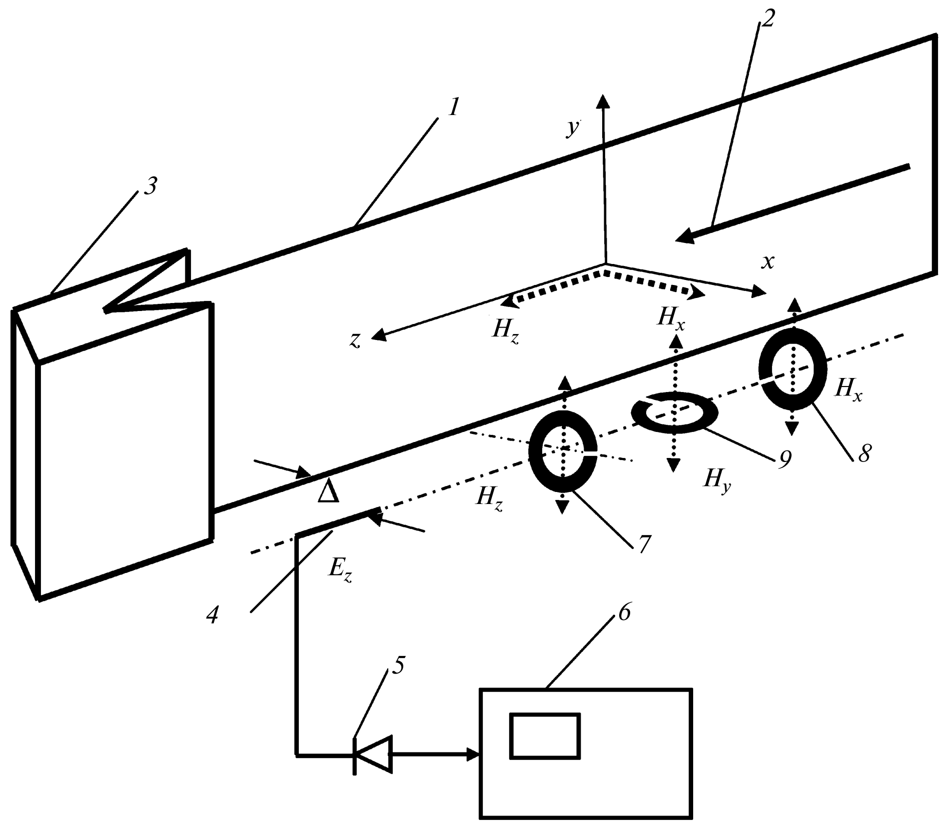

Fig. 7. Layout for measuring the intensity distributions of magnetic components of the field of the surface wave: (*1*) plane of the anisotropically conducting tape; (*2*) forward wave; (*3*) matching load; (*4*) receiving probe for component E_z; (*5*) detector; (*6*) recorder; and (*7*, *8*, and *9*) sensors of field components H_z, H_x, and H_y, respectively.

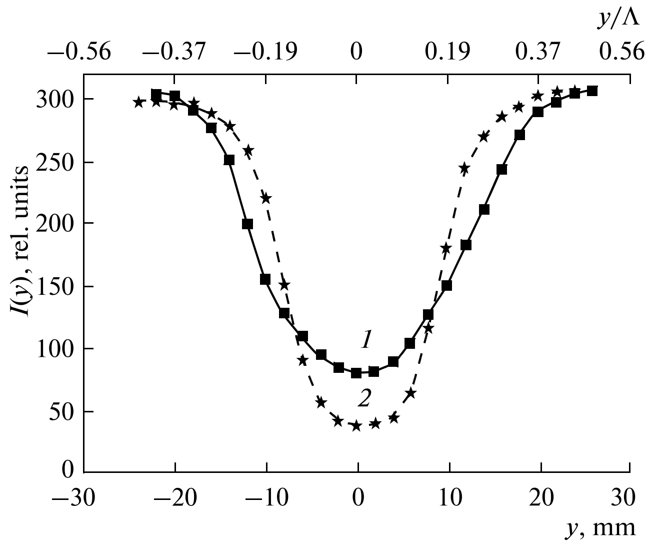

Fig. 8. Readings of the recorder for the case when sensors of magnetic-field components H_z and H_x move along the y axis: (*1*) $\left|E_z^{(0)} - E_z^{(1)}\right|^2$ and (*2*) $\left|E_z^{(0)} - E_z^{(2)}\right|^2$.

The electric signal of this probe enters detector *5* and, afterwards, output recorder *6*.

In this case, intensity distributions of magnetic components were studied with the help of the so-called perturbation method. Let us describe the essence of this method. Data on the analyzed intensities of field components are measured as "perturbations" of the response recorded by the receiver installed at the output of the surface-wave line, rather than the responses of the field probe. These "perturbations" are caused by interaction between a passive magnetic sensor and the corresponding component of the magnetic field. A "sandwich" of two so-called modified broken rings (MBRs) [3] with oppositely oriented radial slots was used as passive sensors of the magnetic field. The MBR sensors were manufactured on a clad dielectric film with the use of the printed-circuit technology. The outer diameter of the rings was ~5 mm, the width along the radius was about 0.7 mm, and the thickness of the dielectric film was 0.12 mm. Dotted arrows in Fig. 7 show the direction of spatial scanning of the rings. Ring *7*, whose plane is perpendicular to vector H_z, creates resonant scattering at the operating frequency $f_0 \simeq 4.1$ GHz. Ring *8*, whose plane

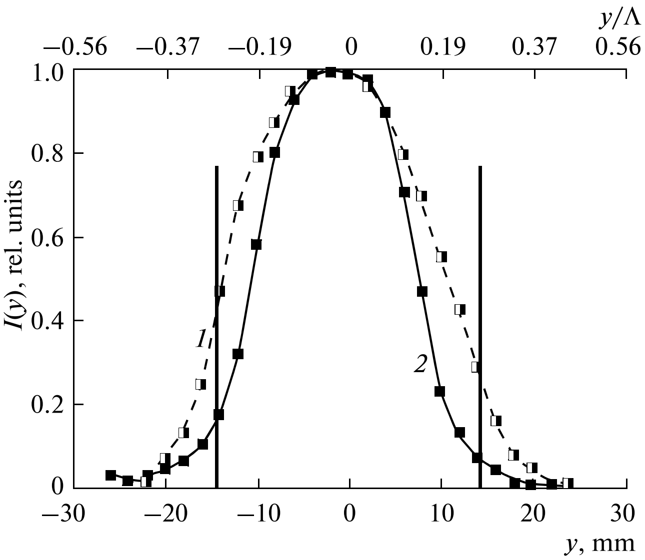

Fig. 9. Intensity distributions $I_m(y)$ of magnetic components of the filed of the surface wave as functions of transverse coordinate y: (*1*) $|H_z(y)|^2$ and (*2*) $|H_x(y)|^2$.

is perpendicular to vector H_x, behaves similarly. Sensors *7–9* in Fig. 7 are shown by outline drawings.

Resonant power extraction performed by rings *7* and *8* causes simultaneous weakening of all three field components. Receiving probe *4* at the output end of the surface-wave line is excited by field component E_z, which is weakened by perturbing influence of rings *7* and *8*, and the degree of this weakening varies as the rings move along the y axis. Curves depicting the readings of recorder *6* (Fig. 7) during motion of rings *7* and *8* along the y axis are shown in Fig. 8. Curve *1* corresponds to variations in the intensity of component E_z under the influence of resonance scattering $E_z^{(1)}(y)$ of ring *7* excited by component H_z. Curve *2* illustrates the behavior of the intensity of component E_z under the influence of resonance scattering $E_z^{(2)}(y)$ of ring *8* excited by component H_x.

It follows from the aforesaid that the degree of influence of responses of rings *7* and *8* to component E_z is proportional to the amplitudes of components $H_z(y)$ and $H_x(y)$. When the rings are shifted beyond the tape ($|y| > 20$ mm), their influence is minimal and, vice versa, when the rings are placed at the tape axis, i.e., at the maxima of $H_z(y)$ and $H_x(y)$, their influence is maximal. In view of these considerations, curves in Fig. 8 can be transformed to normalized distributions $[H_x(y)]^2$ and $[H_z(y)]^2$, which are shown in Fig. 9. Here, vertical lines $y = \pm 14$ mm mark positions of the tape edges. Note that the procedure described above was also used in the study of the influence of ring sensor *9* (see Fig. 7) excited by component $H_y(y)$. It has been found that, as the sensor moves along the y axis, variations in the intensity of component E_z are almost absent.

Thus, as follows from expressions (5)–(7), intensity variations of magnetic components of the field of the surface wave are described by even functions of coordinate y and component H_y is absent.

CONCLUSIONS

An anisotropically conducting tape is a guiding structure supporting slow surface waves. Guiding properties of two tape specimens composed of copper conductors with diameters of 0.12 mm and 0.7 mm have been studied. The tape width is 28 mm and the tape length is about 1 m. In the frequency band 3.5–5.1 GHz, the slowing factor of the surface wave varies from 1.08 to 2.1. The power loss in the tape is about 2 dB/m. The electromagnetic field in the tape has three electric components and two magnetic components. It has been shown experimentally that intensity distributions of components $E_x(y)$ and $E_z(y)$ are described by odd functions, whereas the intensity distribution of component $E_y(y)$ is described by an even function. Intensity distributions of all electric components rather rapidly decrease along the x axis and decrease approximately tenfold at a distance to the tape surface of 20 mm (0.4Λ).

Intensity distributions of magnetic components $H_x(y)$ and $H_z(y)$ are described by even functions and decrease by more than 20 dB at a distance of 10 mm beyond the tape edges. Magnetic component H_y is almost absent in the tape.

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