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Experimental Investigation of the Propagation of Electromagnetic Waves in a Cylindrical Slotted Line

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Results are presented of an experimental investigation of an open transmission line in the form of a partially shielded dielectric rod. Wave types in this line are classified. The delay and attenuation coefficients of each wave mode are determined.

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INTRODUCTION

The well-known open transmission lines, i.e., dielectric waveguides, striplines, periodic lens and reflector structures, make it possible to solve only partially the problem of channelling electromagnetic energy in different wave ranges. Investigation of new types of open transmission lines and the use of their specific properties in engineering is an urgent problem. We present here experimental data on the radiation from one of such lines, i.e., a cylindrical slotted line (CSL) [1, 2]. In these studies a theoretical solution is obtained of the problem of propagation of electromagnetic waves in a round dielectric rod which is partially contained inside a perfectly conducting envelope. The properties of the slot wave inside the slot in such a line were studied in [2-4] for the case of cylinder with a narrow longitudinal slot. Delay, attenuation and structure of the field of this wave were calculated in the approximation of exponentially narrow slot and measured.

There is definite interest in the investigation of the waveguiding properties of transmission lines in the form of partially shielded dielectric rod over the entire range of variation in the angular dimensions of the slot from 0 to 360 degrees. In the modal composition of such structure, as well as in other metal-dielectric waveguides [5] one has to expect the presence of slow waves that are due to: 1) the dielectric constant of the rod $\varepsilon > 1$; 2) the finite conductivity of the metallic shield; 3) the slot in the metallic cylinder.

The main characteristics of slow waves (attenuation α, the delay coefficient $U = c/v_{ph}$, where c is the velocity of light in free space, v_{ph} is phase velocity) depend on such

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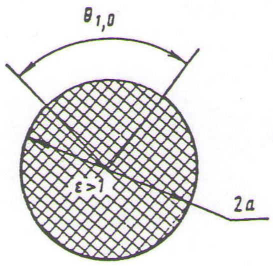

Fig. 1. Transverse cross section of a cylindrical slotted line.

parameters of the structure as the dielectric constant of the rod ε, the radius of the rod a, the angular width of the slot $\theta_{1,2}$ (Fig. 1). It is natural to classify the wave types of a partially shielded dielectric rod according to the degree of this dependence. The effect of the structural parameters on the transmission line characteristics in the regime of one of the waves changes in different angular dimensions of the slot and, therefore, the classification used is somewhat conventional in nature.

1. THE WAVES INSIDE A CYLINDRICAL DIELECTRIC-FILLED WAVEGUIDE

The limiting values of the angular width of the slot of a partially shielded dielectric rod correspond in this case to a round dielectric waveguide, and in the other case to a round metallic dielectric-filled waveguide. In the longwave region ($\lambda > 3.41\sqrt{\varepsilon}a$) the latter does not transfer energy in the inner space. However, in the outer space this structure can carry Sommerfeld's wave because of the finite conductivity of the metallic envelope [6].

The presence of a narrow slot in the cylinder results in the appearance of slot wave H_{00}. The delay coefficient of such wave can be calculated from the formula [7]

$$U=\left[\frac{1+\varepsilon}{2}+\frac{1}{2}(ka)^{-2}\ln^{-1}\sin\frac{\theta_{1,0}}{4}\right]^{1/2}, \tag{1}$$

where $k = 2\pi\ \lambda$ is the wave number in the free space.

The fundamental wave of a found dielectric waveguide is the HE_{11} wave [8]. A narrow metallic strip on the lateral surface of a dielectric rod eliminates the polarization degeneration of the HE_{11} wave. Two waves, denoted in the following by $H^+E_{11}^-$ and $H^-E_{11}^+$, have orthogonal prevailing transverse components of vectors **E** and **H**, respectively (Fig. 2,a,b). The following expressions were obtained for the delay coefficients of the above waves:

$$U=\left[1+\frac{z^2}{k^2a^2}\right]^{1/2}, \tag{2}$$

$$\text{for}\quad H^-E_{11}^+\quad z=z_0\left(1+\ln^{-1}\varkappa\frac{\varepsilon+1}{k^2a^2(\varepsilon-1)}\right), \tag{3}$$

$$\text{for}\quad H^+E_{11}^-\quad z=z_0\left(1-\varkappa^2\frac{2(\varepsilon+1)}{k^2a^2(\varepsilon-1)}\right), \tag{4}$$

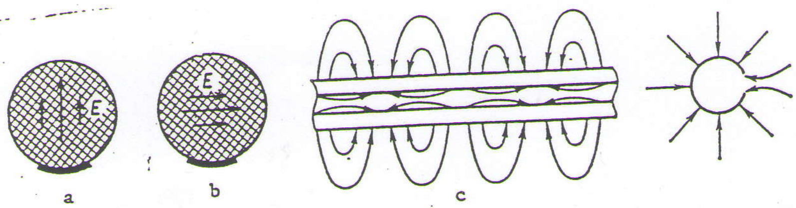

Fig. 2. Polarization of waves in a cylindrical slotted line: a) $H^-E_{11}^+$; b) $H^+E_{11}^-$; c) Sommerfeld wave.

= strip mode in later publications

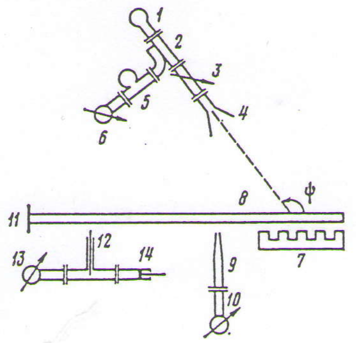

Fig. 3. Schematic of the experimental setup.

where

$$z_0 = \frac{2}{\gamma}\exp\left\{-\frac{\varepsilon+1}{k^2a^2(\varepsilon-1)}+\frac{\varepsilon+1}{8}\right\},$$

$$\varkappa=\cos\frac{\theta_{1,0}}{4},\quad \gamma=1{,}7811.$$

Note that in the derivation of formulas (2)-(4) the following assumptions were made

$$\varkappa^2\ll 1,\ k^2a^2\sqrt{\varepsilon-1}\ll 1,\ z^2\ll k^2a^2(\varepsilon-1). \tag{5}$$

It is of interest to follow experimentally the dynamic behavior of the conversion of waves of a round dielectric waveguide with a narrow metallic strip into waves of a dielectric-filled cylinder with a slot in order to obtain data on actual specimens with a metallic envelope of a finite conductivity and thickness. The method of investigation does not change when passing from one specimen or wave type to another.

2. EXPERIMENTAL INVESTIGATION OF A CYLINDRICAL SLOTTED WAVEGUIDE

A partially shielded dielectric rod was investigated in the millimeter wave range. This wave range was selected, because it makes it possible to realize simply the diffraction input of energy into the open transmission line and, therefore, a selective excitation of the investigated wave [9].

Figure 3 shows the schematic of the experimental setup. Through a horn antenna 4 and diffraction grating 7 oscillator 1 excites a surface wave in the investigated specimen 8. The longitudinal distribution of the field in the line is picked up by probe 9 or 12. Signal from detector 10 (13) via an amplifier enters a recorder. Amplitude calibration of the graphs was achieved using a calibrated attenuator 3. The standing-wave regime was established in the line by a short-circuiting metallic plate 11. Wavelength was measured using a resonant wavemeter 5 that was connected between directional coupler 2 and detector 6. Probe 12 was tuned to resonance, indicated by the maximum of the signal in detector 13, by moving the shorting plunger 14.

Excitation and reception of the investigated wave was ensured by a suitable choice of the diffraction grating, setting the necessary excitation angle ψ, and of the polarization of the horn antenna and the receiving probe type. The totality of the above procedures made it possible to selectively excite the partially shielded dielectric rod with a mode purity of 20-40 dB in the presence of another wave type with orthogonal polarization and a purity of 10-20 dB in the presence of waves of the same polarization as the one investigated. The transverse components of the electric field were investigated using a coaxial probe 12 with a quarter-wave dipole at its end. The diameter of the inner conductor was 0.15 mm. The longitudinal components were investigated using the narrowed end of waveguide 9 with a coupling slot of width 0.1 mm and thereby a high resolution could be obtained for a working wavelength $\lambda = 4.1$ mm.

From the measurement of the longitudinal distribution of the field in the regime of high standing-wave ratios, we obtained the wavelength inside the line (the period of beats of the forward and reflected waves was equal to one-half of the wavelength in the line). The working travel of the probe in the setup was ≈200 mm so that we could measure the wavelength in the investigated specimen with an accuracy of ±0.25%. The oscillator wavelength was measured with

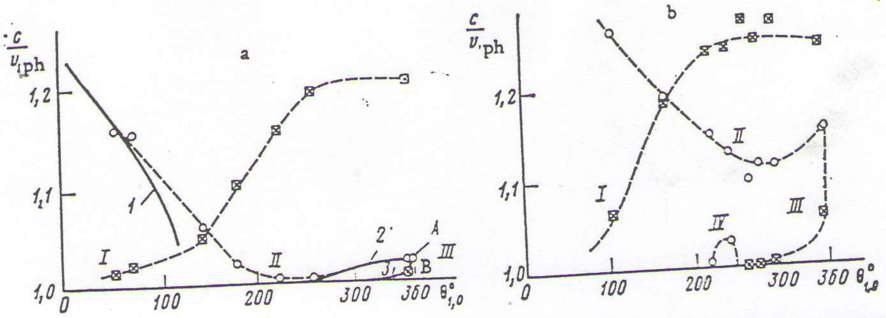

Fig. 4. Curves of the delay coefficients vs. the angular width of the slot: solid curves are theoretical and the dashed curves are experimental: circles — H waves; squares — E waves.

the aid of a resonant-type wavemeter; under these conditions the total error in the determination of the delay coefficient was ±0.5%.

3. DISCUSSION OF THE EXPERIMENTAL RESULTS

Figure 4, a,b shows curves of the delay coefficients of the natural waves of the partially shielded dielectric rod vs. angular width of the slot for specimens of two types (of a diameter 1.5 and 2.3 mm, respectively). For the dielectric material we used polyethylene ($\varepsilon = 2.25$, $\mathrm{tg}\,\delta = 0.5 \cdot 10^{-3}$). The metallic envelope was made of copper foil of thickness $d = 0.05$ mm.

Branch I in Fig. 4,a corresponds to a wave with dominant longitudinal currents on the metallic strip (Fig. 2,c). This wave was excited by a diffraction grating of the comb type with narrow slots. Vector H of the incident wave was parallel to the grating slots. The narrowed end of the waveguide was used for the probe. When the dielectric rod was completely shielded ($\theta_{1,0} \to 0$), branch I corresponds to Sommerfeld wave with a very small delay due to the finite conductivity of the copper envelope. The presence of the slot and its increase result in a great delay of the Sommerfeld wave on account of the dielectric. The delay coefficient becomes greatest when the width of the strip is minimum. In this case, the shielding of the rod is minimum and, moreover, the finite conductivity of the metal, as in the case of a round conductor of a small radius, has a greater effect.

Curve II in Fig. 4,a corresponds to a wave with dominant transverse components of vector E. This wave was excited by a diffraction grating of the comb type with wide slots. Vector E of the incident wave is in parallel to the slot in the grating. For the indicator we used a coaxial probe with a quarter-wave dipole. The strong shielding of the dielectric rod results in energy being mainly transferred in the slot region. In connection with this, it is natural to call this wave a slot wave [1-3]. Curve 1 in Fig. 4,a depicts the slot wave delay coefficient as calculated from formula (1). In the region of widths of the slots $\theta_{1,0} < 80°$ we observe a good agreement between the theory and experimental values. Further on, we observe a strong divergence which can be explained by the approximate nature of the formula that was obtained for narrow slots and small radii of the dielectric rod.

The slot wave delay monotonically decreases with increasing slot width up to $\theta_{1,0} = 200°$–$220°$ and thereafter the H_{00} slot wave continuously changes into the $H^{+}E_{11}^{-}$ wave and its delay increases up to the value of the delay of the HE_{11} wave in a round dielectric waveguide. Curve 2 in Fig. 4,a depicts the delay coefficient of the $H^{+}E_{11}^{-}$ wave as obtained from formulas (2), (4). Good agreement between the theoretical and experimental data can be observed.

Branch II in Fig. 4,a corresponds to the $H^{-}E_{11}^{+}$ wave. Curve 3 in Fig. 4,a depicts the delay coefficient as a function of angular width of the slot as calculated from formulas (2) and (3). Two experimental plots A and B for values $\theta_{1,0} = 360°$ and $356°$ are shown. The $H^{-}E_{11}^{+}$ was excited like the excitation of Sommerfeld's wave and the narrowed end 9 of the waveguide was used as a probe.

One must note that branch II in Fig. 4,a is the region of angles $\theta_{1,0} = 220°$–$240°$ corresponds to very small delay coefficients ($U \approx 1.005$). Transition of the slow surface wave into fast escaping wave can quite possibly occur in the intervals between the experimental plots. In order to be able to answer unambiguously whether the H_{00} slot wave and the $H^{+}E_{11}^{-}$ wave are the same wave, we conducted a series of experiments with a partially shielded dielectric rod of a large diameter — to wit, $2a = 2.3$ mm.

With all other conditions kept the same, higher values of parameter ka must correspond to great delay coefficients of surface waves. This is corroborated in Fig. 4,b that shows

Table

Wave type	Parameters			
	$2a$, mm	$\theta^0_{1,0}$	α experi., dB/m	α calc. [3], dB/m
Sommerfeld wave	2,3	107	1,93±0,27	—
	1,35	33	26	
Slot wave	1,5	74	2,8±1,5	—
	1,35	33	5,0±0,5	6,98

experimental data similar to those in Fig. 4,a. As it follows from Fig. 4,b (branch II), the slot wave continuously passes into the $H^+E_{11}^-$ wave in the region of angles $\theta_{1,0} = 240°-300°$. A somewhat greater spread in the experimental plots in comparison with the case of a rod of diameter $2a = 1.5$ mm can be observed which is explained by greater errors in the fabrication of the specimens. The delay coefficients calculated from formulas (1)-(4) are in agreement with the experimental values within 5%.

Together with the considered waves, one of the higher wave types is produced in the region of angles $\theta_{1,0} = 220°-250°$ (Fig. 4,b, branch IV). The polarization of this wave is the same as that of the $H^+E_{11}^-$ wave and excitation and reception of the former was achieved in a similar manner as of the latter.

In addition to the above methods of determination with respect to excitation angle ψ and the standing-wave period, the modal composition of the investigated specimens was controlled in the measurement process with respect to the period of the spatial beats between the different wave forms. The period of beats between two waves propagating in one direction with propagation constants γ_1 and γ_2 is equal to $\Delta y = 2\pi/\gamma_1 - \gamma_2$. This method exhibits a high sensitivity: the pattern of beats can be readily discernible when two waves with amplitudes differing by up to 25 dB are excited.

4. ATTENUATION OF WAVES IN A SLOTTED WAVEGUIDE

Attenuation is an important characteristic of transmission lines. The feasibility of selective excitation and reception of one wave type made it possible to determine attenuation of each of the waves of a partially shielded dielectric rod.

Attenuation was determined from the measured values of the standing-wave ratio ρ at the beginning and end of a long-line section L. The working formula has the form

$$\alpha = \frac{8{,}68}{2L} \ln \frac{[\rho(L)-1][\rho(0)+1]}{[\rho(L)+1][\rho(0)-1]} \text{ (dB/m)}. \tag{6}$$

This method has advantages in comparison with the method of determining losses from field intensity drop along the line since the former does not require exceptionally accurate adjustment of probe displacement along the line.

The Table shows some values of the measured attenuation coefficients α and calculated according to [3] for the slot wave. In the case of narrow slots we observe a good agreement between the theoretical and experimental values.

The high losses of Sommerfeld's wave in the specimen for $2a = 1.35$ mm, $\theta_{1,0} = 33°$ can be explained by the fact that the attenuation coefficient of this wave $U \approx 1$ and the wave is readily radiated from inhomogeneities of an actual specimen.

By producing artificial weak inhomogeneities in a cylindrical slotted line we can realize different constructions of diffraction filters for the slot wave. For such inhomogeneities we can use bent sections of the line [8]; a periodic variation in the slot width; a diffraction grating with narrow slots, well radiating waves with longitudinal components of vector E, and placed at a distance of $\sim\lambda/2$ from the cylinder surface. Such diffraction filters radiate readily surface waves with a small delay and it is therefore desirable to choose the design width of the slot within the limits $\theta_{1,0} \leqslant 80°-100°$, where the delay of the Sommerfeld wave is very small and the delay of the slot wave is maximum.

In practical usage of a cylindrical slotted line diffraction filters must be used only when the ratio of the slot wave amplitude and Sommerfeld amplitude at the exciter output, or at the output of any other functional unit, is unsatisfactory. The diffraction input ensures, as a rule, the required modal composition purity.

SUMMARY

In calculation of the dispersion of waves in a round dielectric rod with a perfect metallic envelope [1-3] it was established that one fundamental wave type, i.e., the H_{00} slot wave, is produced when the slot is narrow ($\theta_{1,0} \to 0$) and two waves $H^{+}E_{11}^{-}$ and $H^{-}E_{11}^{+}$ are produced when the strip is narrow ($\theta_{1,0} \to 360°$). These concepts were substantially corrected by experimental studies. It turned out that the H_{00} slot wave continuously changes into the $H^{+}E_{11}^{-}$ wave when the slot width increases from 0 to 360°. Together with the presence of the above waves there is always the possibility of propagation of a Sommerfeld-type wave due to the finite conductivity of the metallic envelope as well as to $\varepsilon > 1$. It is characteristic that the delay of Sommerfeld's wave occurs within the same interval as that within which occurs the delay of the fundamental wave $H_{00} - H^{+}E_{11}^{-}$, only it increases rather than decreases with increasing $\theta_{1,0}$. As to attenuation, for Sommerfeld's wave it can be somewhat smaller than for the $H_{00} - H^{+}E_{11}^{-}$.

Sommerfeld's and fundamental wave of a partially shielded dielectric rod turned out to be quite satisfactory with regard to attenuation and delay (particularly in the region of high slot apertures). The different nature of these waves manifests itself in the considerably different field structure. This fact offers a possibility for selective excitation which is of no little importance for applications in millimeter-wave engineering. One must note that apparently we can investigate Sommerfeld's wave only experimentally in the transmission line since at present the development of a rigorous theory of propagation of waves in a rod with a nonideal envelope encounters considerable difficulties and to overcome them is one of the important problems in diffraction theory.

Thus, we experimentally investigated a transmission line in the form of a partially shielded dielectric rod. The modal composition, delay and attenuation in the long-wave region are determined. Delay of the waves in such transmission line can be varied within wide limits by suitable choice of the structure parameters. Attenuation turned out to be quite acceptable for building functional units and elements on the basis of a cylindrical slotted line in the millimeter-wave range.

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