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CALCULATION OF A MULTILAYER DIALECTRIC WAVE GUIDE.(U)

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CALCULATION OF A MULTILAYER DIALECTRIC
WAVE GUIDE

by

G. D. Rozhkov, A. S. Belanov,
V. F. Vzyatyshev

EDITED TRANSLATION

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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

Section 4. DIELECTRIC WAVE GUIDES: CALCULATION OF A MULTI-LAYER WAVE GUIDE

G. D. Rozhkov, A. S. Belanov, V. F. Vzyatyshev

ON THE APPLICATION OF DIELECTRIC WAVE GUIDES IN A SUB-MILLIMETER WAVE RANGE

At this time there are several factors which prevent the widespread application of dielectric wave guides (DV) in a submillimeter wave range. The basic factors appear to be attenuation and the necessity of reducing the lateral dimensions of the DV in order to maintain a single wave regime.

Attenuation in DV, although slower than in hollow metallic wave guides, is increased with a shortened wave length. With current materials with a loss angle on the order of $2 \cdot 10^{-4}$ for single wave wave guides*, it reaches 6 + 10 db/m, somewhere on the border between the ranges of millimeter and submillimeter waves.

In connection with this, for the application of DV in a submillimeter wave range, it is necessary, primarily, to achieve a substantial reduction of attenuation in them. One of the possible ways of solving this problem involves the use of DV made from special materials. In fact, owing to the peculiarity of the propagation mechanism in DV (62), the basic cause of attenuation appears to be in heat losses in the material of the wave guide, so that the attenuation is proportional to the loss angle of the material.

*) They exist in the form of DV with a significant slowing down, which can be subjected to bends and twists.

Is it possible to lower the loss angle of materials in the millimeter and submillimeter wave ranges? Specialists on the electrical properties of dielectrics think that such possibilities do undoubtedly exist (63). As far back as 1964 a polyethylene was derived with $tg\,\delta = 2.7 \cdot 10^{-5}$ at a frequency of 55.2 Giga cycles per second (64). If such a loss angle was maintained up to a frequency of 300 Giga cycles per second, then DV from this material would have attenuation of around 1 db/m for a wave length of 1 millimeter.

Recently a report was published concerning work being done by several English firms aimed at finding special materials for DV, having significantly smaller losses in the submillimeter wave range, than in well known materials. In (65) is a discussion of the first achievements in this direction.

Nevertheless, even if materials were obtained with small losses, difficulties remain which are connected with the small dimensions of the cross section. It will be difficult to implement such DV with the fulfillment of necessary allowances. Besides this, with the small dimensions of the DV the junction of the wave guide outlets of the separate nodes is hindered during the assembly of devices made from them.

Specific difficulties are caused by the fact that the approach to the DV, for example, for the purpose of fastening, of each of the external subjects disturbs the inner electromagnetic field and causes additional losses and emission. In the millimeter range satisfactory solutions have been found to the problem of fastening with the help of elements made from foamy materials, and also with the help of metallic elements. In the submillimeter range elements made from foamy materials can become impracticable because of commensurability of the dimensions of their pores and wave length, and in metallic elements the fastenings excessively increase the ohmic losses.

As long as the same DV, especially when made from polymer materials, have little hardness, it becomes extremely difficult to ensure the mechanical rigidity of the devices in the DV, and also to ensure the stability of the relative location of the DV in the sections of the distributed connection.

It is known (66) that in order to maintain a single wave regime, one should not exceed a certain critical value for higher wave modes of the so called reduced size $\tilde{d} = d\sqrt{\varepsilon_1 - \varepsilon_2}/\lambda$ in DV. (1)

From (1) it follows that it is possible to increase the physical dimensions of DV, d, if the dielectric constant of the material of the DV, ε_1, is reduced. Unfortunately, the minimal value of ε of known uniform hard dielectrics is close to 2. The use then of porous materials like foamy polystyrene is difficult because of the necessity of deriving the pores by the diameter, of a significantly lower wave length, and also because of insufficient rigidity of the latter.

Nevertheless there is another possibility of raising the lateral dimensions of the DV. It involves the increase of the dielectric constant of the environment of ε_2 in (1). In practice this corresponds to the transition to a multilayer DV.

Multilayer DV

The simplest example of such a DV is a bar made from material with ε_1 in a massive uniform casing made from material with ε_2. If such DV are made, for example, from polyethylene (ε_1= 2.28) in a teflon casing (ε_2=2.08), the lateral dimensions of the polyethylene bar might be increased approximately 3 times in comparison with the case of its disposition in air (ε_2 = 1).

With the use of the multilayer DV it is easy to also solve the problem of fastening, as long as the field in the casing is quickly dampened during removal from the bar. The problem of the junction is also alleviated. Nevertheless if the casing surrounds the bar of the DV on all sides, access to the inner field of the DV is hampered, and also the control of the parameters of the devices with the distributed connection.

One must not forget, that together with the useful effect - the increase in the lateral dimensions of the guide bar and area of the field - of the DV the guiding properties deteriorate in the casing. They can be characterized by the value of slowing down ξ_2 with respect to the environment, which can not be more than the value $\beta_{2M} = \sqrt{\varepsilon_1/\varepsilon_2} - 1$, and in a single wave regime, as a rule, does not exceed the value $\beta_{20} \approx \beta_{2M}/2$. For example, in the variant of the polyethylene-teflon DV discussed above $\beta \leq \beta_{20} \approx 2\%$.

The poor guiding properties of the multilayer DV are revealed in the fact that emission in the bent sections will occur even with extremely large radii of the curvature. The most significant might appear to be the fact that the total (for emission and heat) angle attenuation in the bent section with radius R $\alpha_{\Sigma\theta} = \alpha_i + \alpha_T R$, (2) as was shown in (66), can not be less than certain minimal value $\alpha_{\Sigma\theta\,min}$, attainable with an optimal bend radius R_{opt}. We shall make an appraisal of these values.

For the angle attenuation owing to the emission in db/rad from (66, 67) we have $\alpha_i = 55R'\beta_2 \exp(-11.8R'\beta_2^{3/2})$, (3)
where β is the slowing down of the wave with repect to the medium $R' = R/\lambda_2$ is the relative radius of the bend in wave lengths in the surrounding medium $\lambda_2 = \lambda/\sqrt{\varepsilon_2}$.

For heat loss (in db/unit of length) from (66) it is possible to record $\alpha_T = \frac{27.29}{\lambda_2}\left[\sqrt{\frac{\varepsilon_1}{\varepsilon_2}}\, tg\,\delta_1 k_1 + tg\,\delta_2 k_2\right]$, (4)
where δ_1 and δ_2 are the angle losses in media ε_1 and ε_2; k_1 and k_2 are the structural attenuation factors. In our case $\sqrt{\varepsilon_1/\varepsilon_2} \approx 1$; with this $k_1 + k_2 \approx 1$ irrespective of the form of the profile and dimensions of the wave guide. If we still put $\delta_1 = \delta_2 = \delta$, then the correlation (4) will take the form $\alpha_T \approx \frac{27.29}{\lambda_2}\, tg\,\delta$. (5)

By substituting (3) and (5) in (2) and differentiating according to R, for R'_{opt} we derive $R'_{opt} = 0.0848\,\zeta_2^{-3/2}\,y,$ (6)

where y is the root of the equation $(y-1)e^{-y} = 0.497\,\zeta_2^{-1}\,tg\,\delta.$ (7)

By substituting (6) and (7) in (2), we have (8)

$$\alpha_{\Sigma\theta\,min} = 27.29\,tg\,\delta\,R'_{opt}\,\frac{y}{y-1}\,.$$

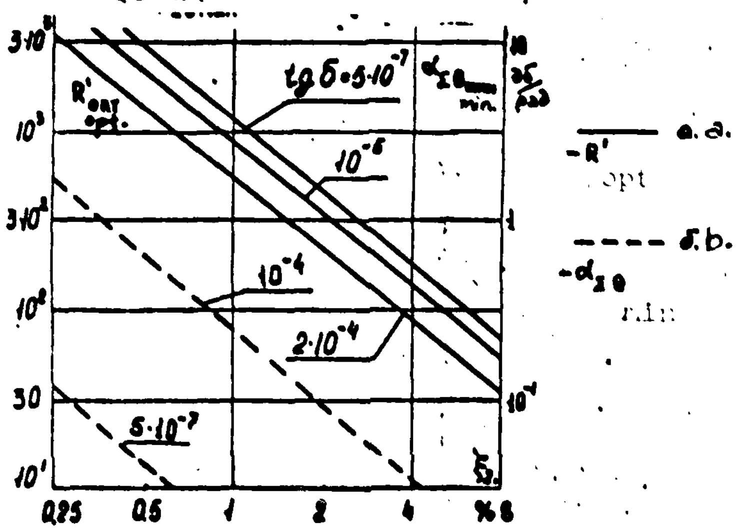


Figure 1

In the graphs of Figure 1 are the variables of the values of R'_{opt} (Figure a) and $\alpha_{\Sigma\theta\,min}$ (Figure b) from the value ζ_2. It is apparent from the graphs that with current materials ($tg\,\delta = 2\cdot10^{-4}$) the minimal losses in the bend all ready with $\zeta_2 < 0.02$ becomes inadmissibly large (more than 2db/90°). The optimal radius of the bend is around $220\lambda_2$ and the acceptable value, obviously, is only in the short wave section of the submillimeter range (with $\lambda = 0.3$ millimeters and $\varepsilon_2 = 2.08$, $R_{opt} = 45$ millimeters).

Losses in the bend can be substantially reduced with the reduction of $tg\,\delta$. Thus, with $tg\,\delta = 5\cdot10^{-7}$ even the value $\zeta_2 = 2.5\cdot10^{-3}$ is fully acceptable, which corresponds to $\varepsilon_1/\varepsilon_2 \approx 1.01$ and will allow us to increase the lateral dimensions approximately 10 times in comparison with DV in air. Nevertheless, the required bend radii ($R'_2 \approx 8\cdot10^3$), obviously, are inadmissible in all the submillimeter range of waves (even with $\lambda = 0.1$ millimeters and $\varepsilon = 2.08$, $R_{opt} = 540$ millimeters).

Thus, by using the simplest variant of a multilayer DV in a situation where it must be subjected to bends, it is possible to realize a substantial (by one order of magnitude) gain in the lateral dimensions only in the optical and near infrared wave ranges, even then on the condition that the loss angle of the materials will not be higher than $10^{-5} \div 10^{-7}$

The transition to multilayer DV with a nonuniform casing will open up the additional possibility of controlling their parameters. By changing the size of the separate areas of the casing and the parameters of their materials, it is possible to change the properties of the DV within broad limits and to obtain such a coupling of them, which is impossible in DV with a uniform casing. We shall call such a multilayer DV with a nonuniform casing "composited."

"Composited" DV

A composited DV is this bar made from material with $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ bounded on several sides with material with ε_2, and on the remaining - with a medium with ε_3, for example, with air. Several examples of such DV are satisfactorily described by the models, shown in cross section in Figure 2.

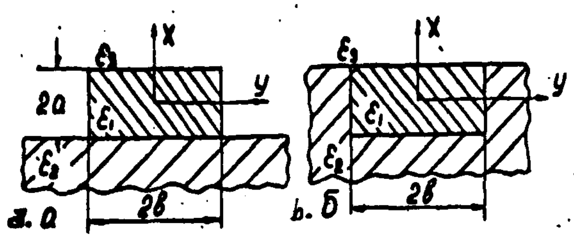


Figure 2

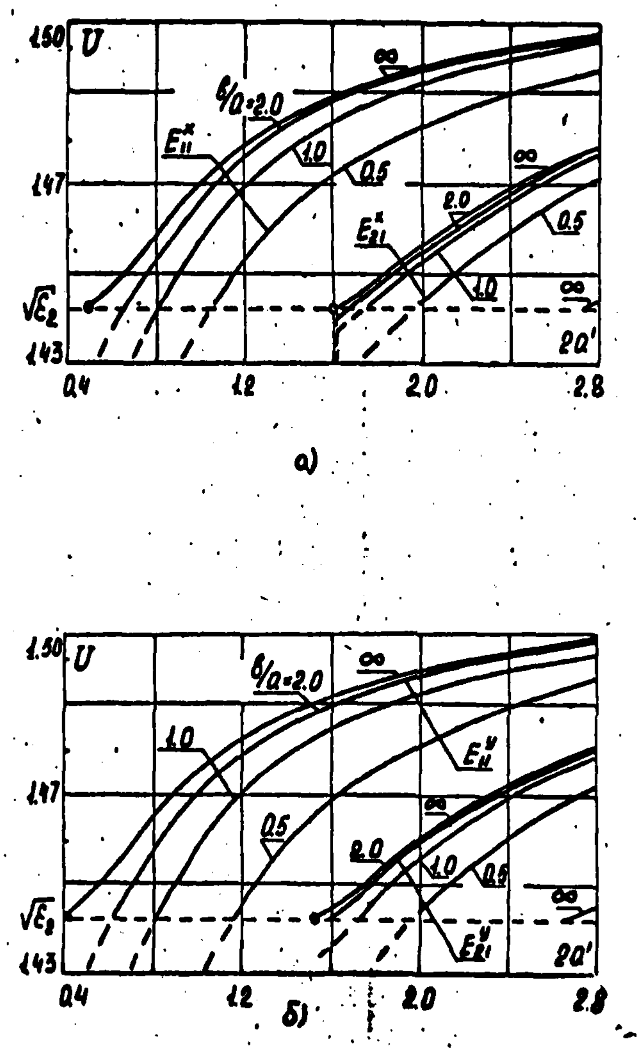
As it will be shown below, examples of the bar of such DV during maintenance of a single wave regime might be taken almost as large as examples of a bar in a uniform casing with ε_2. On the other hand, with $\varepsilon_1 = 1$ such a DV has free access to the internal field. But a more attractive feature is the peculiarity of the behavior of the composited DV in the bent sections. Emission from the bend of such a DV must depend on the direction of the bend. One can expect that the emission from such a bend, during which the free side of the bar is external, is determined by the value of the slowing down ζ_3 with respect to the medium with ε_3. Then the overall dimensions of such a bend can be significantly smaller than in DV in a uniform casing with ε_2.

Unfortunately, rigorous calculation of the characterisitics of composited DV is exceptionally tedious. Because of the presence of additional boundaries of partition, this calculation must be significantly more complex than the calculation of a rectangular DV with a uniform casing. A relatively simple model, which adequately describes such a DV with $\delta >> a$, is the so called nonsymmetric plane DV, representing a layer of dielectric with $\mathcal{E}_1$ with a thickness of $2a$, the medium of on side of which has a dielectric constant of $\mathcal{E}_3$ and from the other - $\mathcal{E}_2$.

Operations (68) and (69) are devoted to an analysis of a nonsymmetric plane DV. We have carried out a numerical solution of the characterisitc equation, and have calculated the wave numbers, the propagation constant, the effective size of the field along both sides from the plate and the structural attenuation factor due to losses in the material of the plate and adjacent media fromthe waves H_1, H_2, H_3, and E_1, E_2, E_3 and the following parameter correlations: $\mathcal{E}_1 = 1.5$; $\mathcal{E}_3 = 1$; $\mathcal{E}_2 = 1$; 1.01; $\mathcal{E}_1 = 2.28$; $\mathcal{E}_3 = 1$; $\mathcal{E}_2 = 1$; 1.05; 1.3; and 2.08; $\mathcal{E}_1 = 3.9$; $\mathcal{E}_3 = 1$; $\mathcal{E}_2 = 1$; 1.05 and 2.08 in the wide range of values presented for the thickness of the plate.

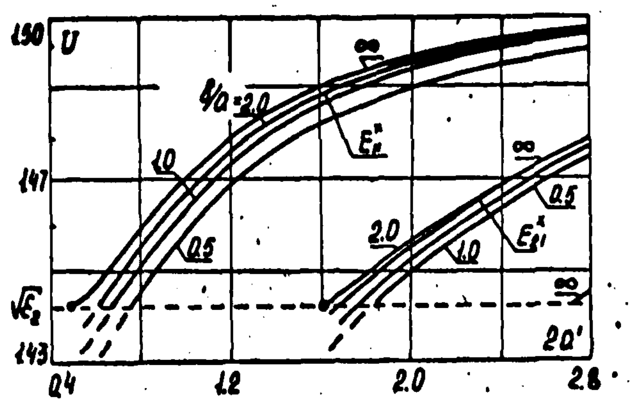
Not being able to present in this work all the results, we shall only carry out the dispersion characterisitics for the case of $\mathcal{E}_1 =$ 2.28 (polyethylene); $\mathcal{E}_3 = 1$; $\mathcal{E}_2 = 2.08$ (teflon). They are noted by the sign ∞ in the graphs in Figures 3 and 4. The upper curves correspond to E_1 wave in Figure a and H_1 wave in Figure b, and the lower ones - accordingly to waves E_2 and H_2. The value U in the graphs is the moderating ratio of the wave with respect to the medium with $\mathcal{E}_3$ - connected with the value discussed earlier ζ_2 in the correlation $U = \frac{c}{v_\phi \sqrt{\mathcal{E}_3}} = (1+\zeta_2)\sqrt{\mathcal{E}_2}$. (9)

As it is apparent from the graphs, the value U complies with the



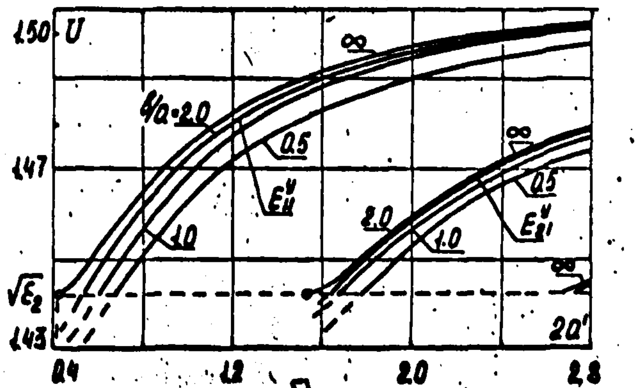
U
1.50
1.47
1.43
$\sqrt{E_2}$
$b/a=2.0$
1.0
0.5
∞
2.0
E^x_{11}
E^x_{21}
2a'
0.4
1.2
2.0
2.8
a)
E^y_{11}
E^y_{21}
б)

Figure 3



U
1.50
1.47
1.43
$\sqrt{\varepsilon_2}$
0.4
1.2
2.0
2.8
2a'
ℓ/a=2.0
1.0
0.5
∞
E_{11}^x
2.0
1.0
0.5
E_{21}^x

a)



U
1.50
1.47
1.43
$\sqrt{\varepsilon_2}$
0.4
1.2
2.0
2.8
2a'
ℓ/a=2.0
0.5
1.0
∞
E_{11}^y
2.0
1.0
0.5
E_{21}^y

б)

Figure 4

inequalities $\sqrt{\varepsilon_2} \leq \mathcal{V} \leq \sqrt{\varepsilon_1}$, (10)

during which the execution of the left equality from (10) corresponds to the critical frequency, while the right - to the infinitely high frequencies. The physical meaning of the left inequality from (10) complies to the fact that the field of the wave in a medium with ε_2 exponentially decreases during removal from the guide bar with ε_1; during its nonperformance the field in the medium with ε_2 will have the form of plane waves, propagated at a certain angle to the axis z and carrying away energy from the guide bar.

The Relative Dimensions and Ranges of a Nonsymmetric Plane DV

Analysis of the critical conditions for the next highest type of wave has shown that the thickness of the plate with parameters, characteristic for the curves in Figures 3 and 4, can be taken 3.5 to 3.6 times larger than the thickness of the plate in air (ε_1 = 2.28; ε_2= 1). It is interesting to note that in the case of a uniform environment (ε_1 = 2.28; $\varepsilon_2 = \varepsilon_3$ = 2.08) it is possible to increase the thickness of the plate only 2.5 times (30% less).

It is also interesting to compare the range properties of the DV under consideration. Considering that the minimal wave length of the range λ_{min} corresponds to the critical conditions of the next highest type of waves and assuming that in the maximal wave length range the slowing down ξ_2 must be equal to a certain minimal value $\xi_{2\,min}$ for the overlap coefficient of the range D = $\lambda_{max}/\lambda_{min}$ we have

$$\mathcal{D} = \frac{d'_{KD}}{d'[\zeta_2 - \zeta_{2\,min}]}. \tag{11}$$

Assuming in the case under consideration $\zeta_{2\,min} = 0.02$, for the nonsymmetric DV we have $D_{H_1} = 1.67$ and $D_{E_1} = 1.58$, whereas for the symmetrical variant $D_{H_1} = 1.56$ and $D_{E_1} = 1.49$ (9 + 11% less).

Thus, the plane nonsymmetric DV exceeds the symmetrical variant both in the allowable lateral dimensions and in the width of the operational range.

Possibilities of an Approximate Calculation

For the calculation of models closer to a real situation in picture 2 it is possible to use an approximate approach, first described by V. Shlosser in (70) and extensively used by Ye. Markatili in (73). It is also thoroughly described in the summary (72). This approach is based on assumptions that the fields in the regions $|x| \leqslant a$; $|y| \leqslant b$ can be described as a single trigonometric function inside the bar and as a single exponential function outside the bar, and it is possible that we will not at all be intersted in the fields in the regions $|x| > a$; $|y| > b$. In (71) it is demonstrated that such an approach will give satisfactory results for small ε_1, particularly in the region far from the critical frequency.

The characterisitic equation derived by the method described can be represented in the form $U^2 = U_H^2 - \left(\frac{\beta}{4\pi\beta'}\right)^2$, (12)

where β is the immeasurable inner wave number (66) of the plane DV with a thickness 2β made from material with $\mathcal{E}_1$ in the case of model 2; U_H is the moderating ratio (with respect to the medium with $\mathcal{E}_2$) of the plane nonsymmetric DV considered above.

The results of calculating the slowing down according to equation (12) for DV with various ratios of b/a are presented in Figures 2 and 4.

The designations of such types of waves are assumed, as in (72) to be the following: the literal symbol (E) indicates the field (in this case, electrical) according to which the direction of polarization is evaluated; the upper letter index (x or y) indicates the axis of the coordinates, in the direction of which, basically, the indicated field is polarized; the lower numerical indices indicate the number of variations of the field in the directions of the respective coordinate axes.

One should expect that the precision of these results will increase with an increase in U. The values of $U < \sqrt{\mathcal{E}_2}$ (the broken line segments of the curves) contradict the physical considerations, as long as the waves, going with the slowing down $U < \sqrt{\mathcal{E}_2}$ must radiate.

Estimations of the width of the operating range according to criterion (11) indicate that it decreases with a decrease in b/a.

With $b/a = 2$ the decrease is small and amounts to $2 \div 7\%$. With $b/a \approx 0.5$ model 2 is significantly more advantageous from the point of view of range properties.

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