https://doi.org/10.38013/2542-0542-2021-2-7-14
UDC 621.372.825

Shielded low-loss metal-dielectric waveguide for frequency range of 90–110 GHz

Krutskilh V. V.[1], Minkara M. S.[1,2], Ibrahim R. A.[3], Mirzoyan A. E.[1], Ushkov A. N.[1]

[1] *National Research University “Moscow Power Engineering Institute” (MPEI), Moscow, Russian Federation*

[2] *Meatel, Beirut, Lebanon*

[3] *College of Science University of Anbar, Ramadi, Iraq*

This study is dedicated to the development of a new design of the shielded low-loss metal-dielectric waveguide for the frequency range of 90–100 GHz. High level of losses in metal is a major challenge complicating implementation of commonly used waveguides in the specified wavelength range. The study objective was to develop the proposal regarding the waveguide design with losses lower than 0.5 dB/m, with persistent wave polarisation. To address the problem, we analysed various waveguide design solutions and estimated losses per unit length along with the possibility to implement the proposed design. We proposed the final variant of waveguide design and selected parameters of structural members to solve the problem at hand.

Keywords: shielded dielectric waveguide, low losses, low-loss waveguide, dispersion characteristic, engineering calculation

For citation: Krutskikh V. V., Minkara M. S., Ibrahim A. R., Mirzoyan A. E., Ushkov A. N. Shielded low-loss metal-dielectric waveguide for frequency range of 90–110 GHz // Journal of “Almaz – Antey” Air and Space Defence Corporation. 2021. No. 2. P. 7–14. https://doi.org/10.38013/2542-0542-2021-2-7-14

Submitted on 17.03.2021 *Reviewed on* 29.03.2021 *Approved on* 27.05.2021 *Published on* 18.06.2021

Introduction

The problem of EHF band wave guidance between devices is not terra incognita to researchers and developers. However, a signal sometimes needs to be transmitted between radio electronic equipment modules separated by a rather long distance (tens of meters). So far, in the range of 30–70 GHz, the problem is supposed to be solved, but at frequencies over 70 GHz there are no appropriate industrial solutions regarding waveguide structures with losses per unit length less than 1 dB/m. According to an analysis of standard waveguide structures such as rectangular and circular metal waveguides, losses may exceed units and tens of decibels per meter in a given frequency range at the primary operating mode. That is why this study analyses other advanced waveguide structures as shown in Fig. 1.

Oversized hollow-type metal waveguides (see Fig. 1*a* and *b*) are similar to standard ones in design, except for larger cross-section sizes. Losses in such waveguides are basically caused by attenuation in metal walls and conversion to higher modes. Beam guides are based on such waveguides [1]. In this respect, any irregularity in such a line may lead to the appearance of higher modes and subsequent losses. Dielectric waveguides (DW) can be viewed as a good solution for implementing a low-loss

---

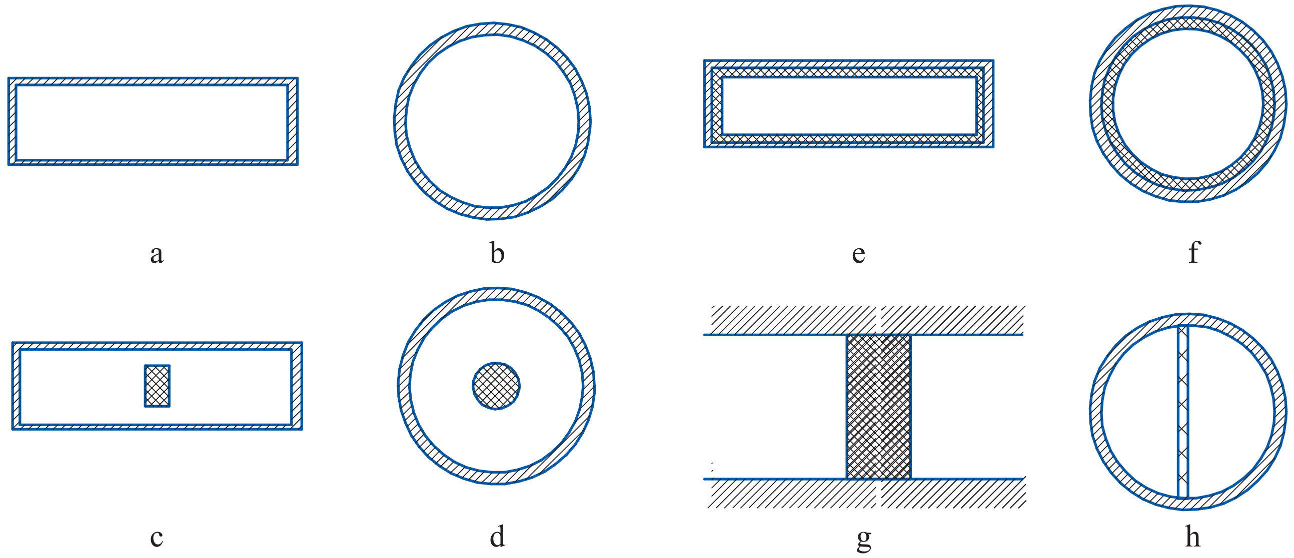


Fig. 1. Cross-sections of waveguide structures

waveguide path in the specified frequency range. Unfortunately, these are open waveguide structures. Placing a dielectric waveguide in an oversized waveguide is a promising solution to the problem. The structures (Fig. 1*c* and *h*) allow to register the primary mode and provide polarization stability. These structures were analysed in [2]. The structures (see Fig. 1*e* and *f)* allow to reduce losses in metal walls, but there are some losses in the dielectric material itself, and such a system shall operate at particular higher wave modes, which shall be properly excited and then disabled. For the waveguide proposed by Tischer (see Fig. 1*g*), losses were calculated in [3] and [4]. Such a waveguide is likely to have relevant losses, but we will not analyse it due to the requirement for complete shielding. Finally, we have three types of structures to be analysed (see Fig. 1*c, d* and *h*).

The application of this particular waveguide path is required for combined interferometers and radiometers to enable simultaneous signal processing in order to determine the distance to and the temperature of the object being measured. Therefore, on the one hand, we shall have appropriate matching and low losses at a given frequency; on the other hand, a sufficiently wide frequency band, including several low-frequency ranges.

1. Estimation of losses in different waveguide structures

To solve the problem, at the fist stage we estimated losses in walls of an oversized metal waveguide (see. Fig. 1*a, b)* for the primary mode. We conducted calculations that allowed to estimate losses in walls of hollow-type rectangular and circular metal waveguides. For this purpose, we used calculation ratios given in [5, 6]. The authors did not analyse the structures of standard metal waveguides for the specified range, a priori knowing that losses at the required frequency were over 2 dB/m.

Oversized waveguides' losses per unit length were calculated for the main wave modes: H_{10} of rectangular waveguide, H_{11} and E_{01} of circular waveguide. Figs. 2 and 3 show the attenuation per unit length – frequency dependencies for series-manufactured oversized copper waveguides of standard cross-sections. According to graphs (see Figs. 2–4), losses increase monotonically as the frequency rises, while a decrease in losses is proportional to the waveguide tube's cross-section area.

Waveguide tubes comply with problem setting if their cross-sections are over 13×6.5 mm for rectangular waveguides (waveguide sizes are selected as per State Standards GOST 17426-72 "Metallic tubing for waveguides" and GOST

“Connectors of microwave channels of radio-measuring apparatus”) as well as with the diameter over 6 mm for circular metal waveguides.

Waveguide attenuation per unit length is calculated by the following formula:

$$\Delta_{пог} \approx 8.686 \cdot h'' \left[\frac{dB}{m}\right], \tag{1}$$

where $h'' = h''_м + h''_{ср}$ – total attenuation coefficient in metal and dielectric-filled waveguide.

Due to losses in walls of a rectangular metal waveguide for magnetic wave H_{mn} the attenuation coefficient is represented in the following form:

$$h''_м = \frac{\sqrt{\frac{\mu_{ам}\omega}{2\sigma_м}}}{b\sqrt{\frac{\mu_a}{\varepsilon_a}}\sqrt{1-\left(\frac{f_{кр}}{f}\right)^2}}\left[\left(1+\frac{b}{a}\right)\left(\frac{f_{кр}}{f}\right)^2\right], \tag{2}$$

where a and b – waveguide cross-section sizes, $\sigma_м$ – metal conductivity, $\mu_{ам}$ – metal permeability.

Due to losses in walls of a circular metal waveguide for magnetic wave H_{mn} the attenuation coefficient is represented in the following form:

$$h''_м = \frac{\sqrt{\frac{\mu_{ам}\omega}{2\sigma_м}}}{r_0\sqrt{\frac{\mu_a}{\varepsilon_a}}}\frac{1}{\sqrt{1-\left(\frac{f_{кр}}{f}\right)^2}}\left[\left(\frac{f_{кр}}{f}\right)^2+\frac{m^2}{\mu_{mn}^2-m^2}\right]. \tag{3}$$

Due to losses in walls of a circular metal waveguide for electric wave E_{mn} the attenuation coefficient is represented in the following form:

$$h''_м = \frac{\sqrt{\frac{\mu_{ам}\omega}{2\sigma_м}}}{r_0\sqrt{\frac{\mu_a}{\varepsilon_a}}}\frac{1}{\sqrt{1-\left(\frac{f_{кр}}{f}\right)^2}}. \tag{4}$$

According to the analysis of losses caused by change of materials, silver coating of the internal shield surface insignificantly reduces losses per unit length by (3–5 %), but makes the product much more expensive.

The second stage was intended to analyse losses in dielectric structures, which were arranged inside the shield, based upon the physical principles of waveguide losses. Losses per unit length in the dielectric medium are estimated by the following formula:

$$P_{пот.пог.диэл} = \frac{\sigma_{ср}}{2}\int_S |\dot{E}|^2\, dS, \tag{5}$$

where $\sigma_{ср} = \omega\varepsilon_0\varepsilon\mathrm{tg}\delta$ – specific conductivity, ε and $\mathrm{tg}\delta$ – dielectric permeability and dielectric loss tangent for filling medium material.

By all means, for a shielded dielectric waveguide it will be more difficult to calculate the dielectric loss power in comparison with a waveguide with continuous uniform filling, while the contribution to total losses will be minor. According to estimations, the heat loss power in polyethylene is lower by 2 orders than that in shield walls, regarding some structures.

The smaller the dielectric rod cross-section sizes, the lower the losses per unit length as per the dielectric waveguide loss calculation procedure given in [7]. According to formula (5), the higher the dielectric permeability, the higher the losses per unit length. With these factors, we can find appropriate solutions for design of a dielectric structure to meet the specified requirements. According to numerical calculation, losses in a polyethylene or fluoroplastic dielectric waveguide become acceptable only if the dielectric waveguide thickness is less than 1 mm.

A semi-shielded dielectric waveguide can be used as the waveguide structure with required losses. Such losses were calculated as per the procedure described in [4]. However, such a variant will not meet the requirement for complete shielding.

Finally, the best suitable solution for the above-mentioned structures is to use a circular oversized metal waveguide more than 6 mm in diameter with wave mode H_{11} that serves as the shield. The advantage of the solution is that mode H_{11} in a circular waveguide is the primary mode and its excitation is not difficult. Polarization instability is supposed to be a major drawback of the solution.

As a result, the following problem can be formulated: for the specified type of waveguide, we shall design a device maintaining

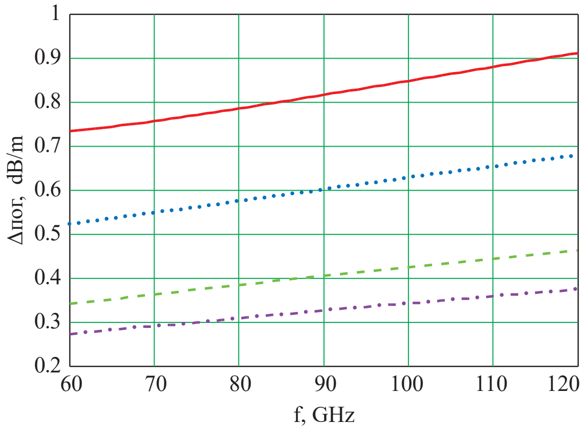


Fig. 2. Dependence of attenuation per unit length on frequency in hollow-type rectangular copper waveguide with primary wave mode H_{10} for different cross-sections:
— – 7.2x3.4 mm; — – 9x4.5 mm;
— – 13x6.5 mm; — – 16x8 mm

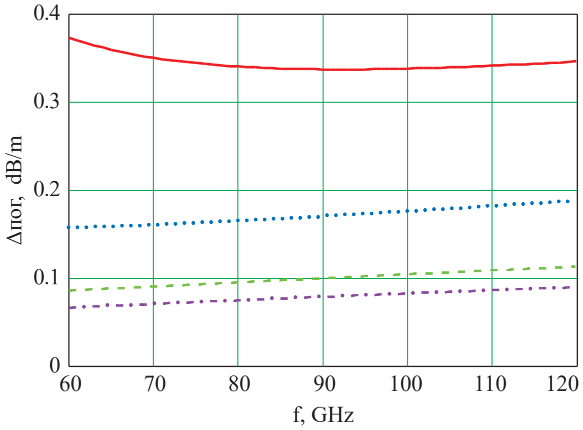


Fig. 3. Dependence of attenuation per unit length on frequency in hollow-type circular copper waveguide for different cross-sections with wave mode H_{11}:
— – 6 mm; — – 10 mm; — – 16 mm; — – 20 mm

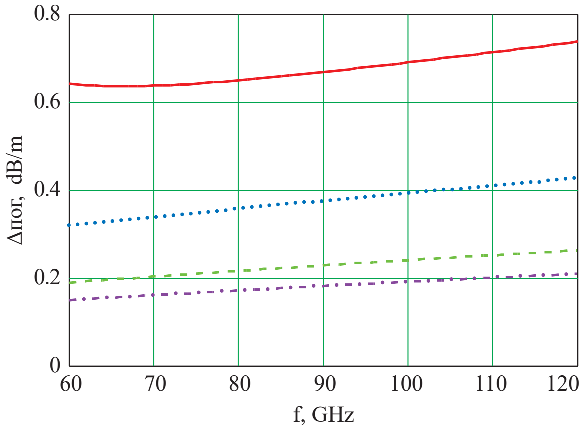


Fig. 4. Dependence of attenuation per unit length on frequency in hollow-type circular copper waveguide of different cross-sections with wave E_{01}:
— – 6 mm; — – 10 mm; — – 16 mm; — – 20 mm

polarization and providing total losses per unit length that do not exceed the allowable value of 0.5 dB/m.

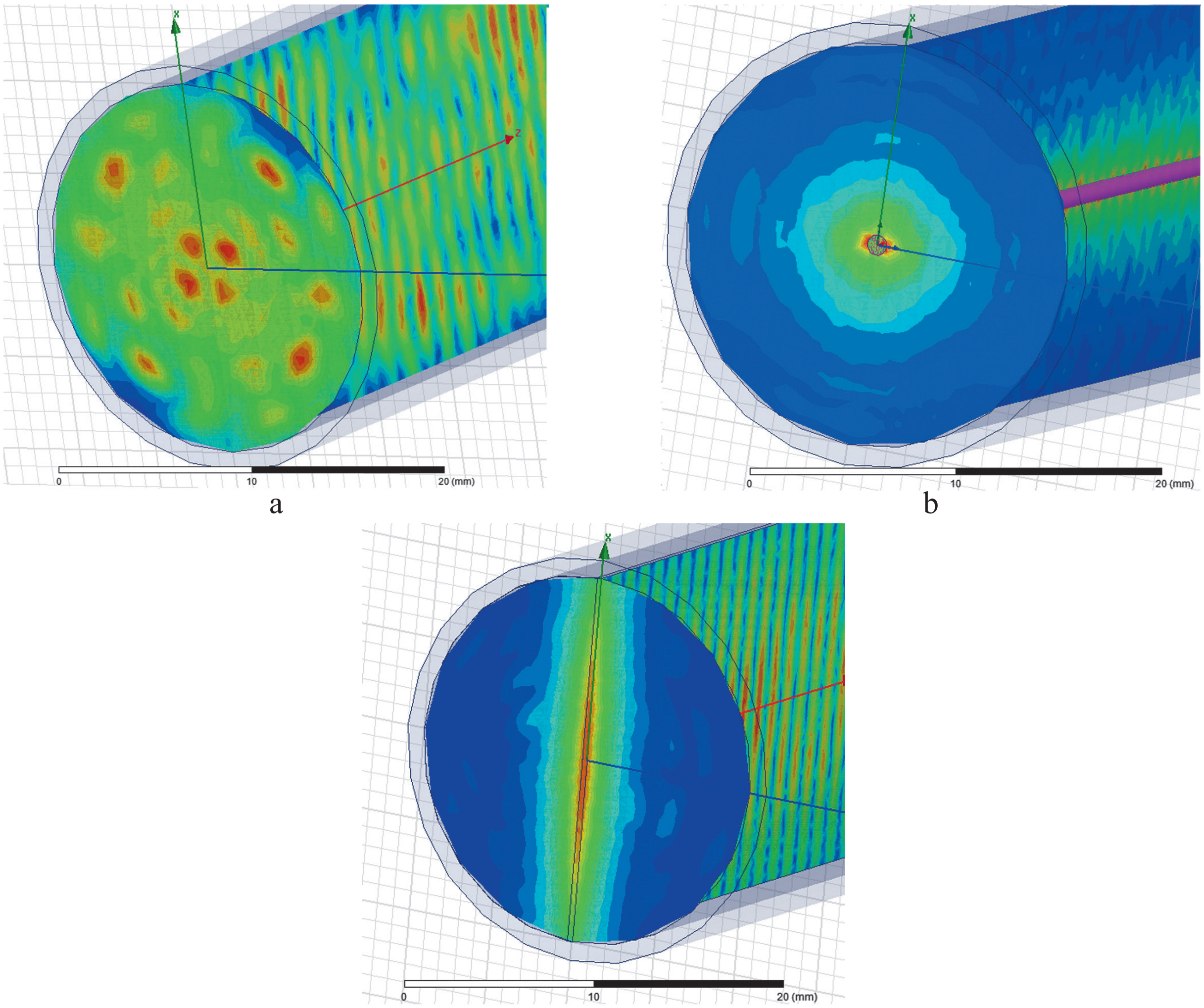
2. Physical principles of loss reduction in metal-dielectric structures

Losses in a conditionally regular (real) waveguide structure comprise heat losses in a metal shield, heat losses in a dielectric structure, polarization losses (due to rotation of the polarization plane) and mode conversion losses. The latter occur only on irregularities and may be decisive in case of a long-distance line. Therefore, in order to reduce the loss level, it is reasonable to reduce the following:

- heat losses in metal – by placing the shield as fas as possible from the maximum electric field distribution;
- heat losses in dielectric structures – by reducing the thickness of dielectric elements and by selecting the element material with the lowest dielectric permeability values and the lowest dielectric loss tangent;
- losses caused by change of the polarization angle – by maintaining the field in the predetermined position using dielectric elements;
- mode conversion losses – by creating a structure, which allows to minimize irregular sections and prevents the formation of local irregularities (for example, joint gaps).

3. Shielded low-loss waveguide design solutions

Fig. 5*a* shows simulated field distribution in an oversized waveguide of 20 mm in diameter. Excitation was made by wave H_{11}. According to field distribution, this waveguide will have a multimode regime not suitable for solving the problem at hand. That is why we will not further discuss this structure. However, we must add that the losses calculated by accurate formulas from [6]



a

b

c

Fig. 5. Field distribution in cross-section of circular copper waveguide of 2 mm in diameter upon excitation of wave H_{11} without rod (a), with dielectric rod of 1 mm in diameter (b) and with 0.2 mm thick dielectric plate (c)

and the software-simulated losses for a 1 m-long section differ by 30–40 %. Such a difference is caused by higher wave modes and rotation of the polarization plane in the computational model.

Based on the physical phenomena and the analysis of dielectric elements, we decided to study some design solutions:

- coaxial structure with a circular dielectric rod in the centre of the circular metal shield (see Fig. 1*d*);
- structure with a dielectric plate in the symmetry plane of the circular metal shield (see Fig. 1*h*);
- hybrid structure including a rod and a thin plate made of dielectric material in the symmetry plane of the tube.

The inherited advantage of the first structure is that it uses two standard waveguides: circular metal and dielectric waveguides. Theoretically, it is easy to implement such a structure, but it is more difficult to implement it in terms of technology. After analysing ratios of dimensions and losses for numerical experiment, we selected dielectric rods of 0.1 to 1.5 mm in diameter. Fig. 6 shows the results of simulation of attenuation per unit length. We should note that for a rod of 1 mm in diameter (1/3 wavelength) and for a shield of 20 mm in diameter, losses per unit length in the investigated frequency band are 0.4 to 0.55 dB/m and they increase if the frequency exceeds 96 GHz.

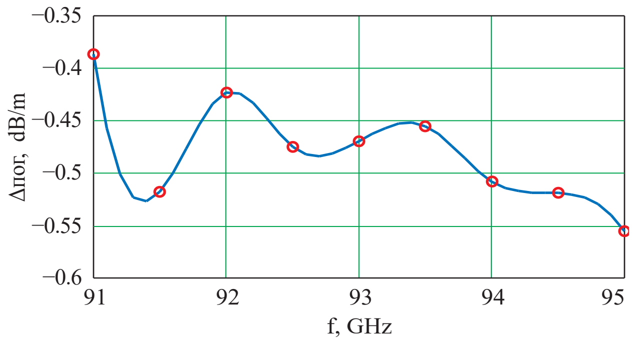


Fig. 6. Attenuation per unit length – frequency dependence for circular shielded dielectric waveguide with rod of 1 mm in diameter and shield of 20 mm in diameter: — – calculation; — – interpolation

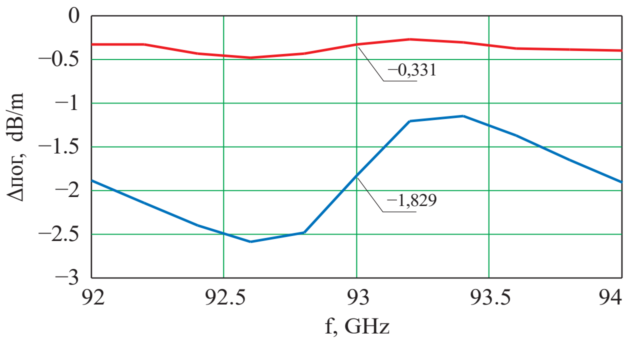


Fig. 7. Attenuation per unit length – frequency dependence for circular copper waveguide with longitudinal dielectric plate located in symmetry plane: — – 0.2 mm film; — – 0.6 mm film

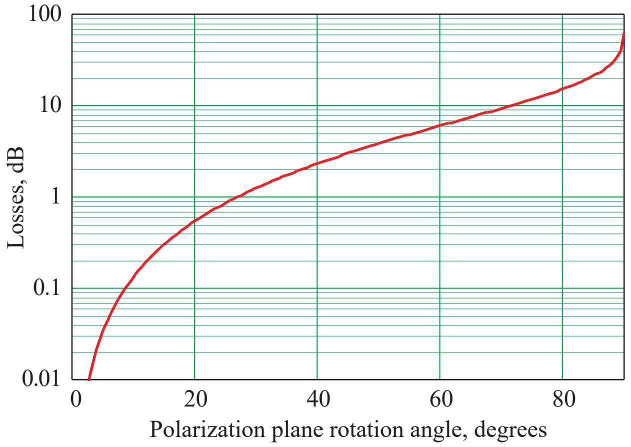


Fig. 8. Dependence of extra losses on polarization plane angle in circular waveguide

In terms of manufacturability, the second structure seems to be more complicated, but implementable in laboratory conditions. A dielectric plate is clamped between two halves of a shield tube with the longitudinal cut. Fig. 1*h* shows the cross-section of the structure; Fig. 5*c* shows field distribution *E*. Distributions show that the field is pressed to the symmetry plane of the metal shield. There is a minimal field near the metal shield, and losses in the dielectric plate make a major contribution as shown in Fig. 7. According to experimental data, the dielectric plate thickness shall be less than 0.2 mm to comply with problem settings. This figure is less than 6 % of the wavelength at the specified frequency in polyethylene. Such a dielectric waveguide is called the low attenuation waveguide, which is thoroughly studied in the theory of dielectric waveguides [7]. Knowing that the shield sizes exceed 3–5 wavelengths, we can apply the theory of loss calculation to the infinite dielectric plate in a semi-shielded dielectric waveguide [4].

4. Extra loss estimation

Losses caused by rotation of the wave polarization plane along with losses caused by energy transfer to other modes can be classified as extra losses. Total losses in the waveguide can be estimated by the following formula:

$$\Delta_{\Sigma} = (\Delta_{мет} + \Delta_{диэл}) + \Delta_{пол} + \Delta_{мод}. \tag{6}$$

Losses caused by rotation of the polarization plane and low irregularities can be estimated using the loss – polarization plane rotation angle dependence graph (Fig. 8). This graph is based on the geometry, provided the receiving and transmitting sections are installed in the same plane and if there is some smooth irregularity that contributes to rotation of polarization plane inside the waveguide.

Loss estimation due to loss conversion turns out to be a challenging problem that requires instantiation of the irregularity type. This study does not cover the said problem.

Conclusions

1. As a result of our work, we have found out that there is the possibility to implement a closed-type electromagnetic waveguide path in the range of 90 to 110 GHz featuring the structure

shown in Fig. 1*h*, or the structure combining the solutions shown in Figs. 1*d* and *h*.

2. The best suitable shield design solution for the above-mentioned waveguide path is a copper tube with the diameter equal to 6 or more wavelengths.

3. The dielectric plate thickness may vary in the range of 3 to 6 % of the operating wavelength.

4. Wave H_{11} of circular metal waveguide (or H_{10} of rectangular one) is considered the operating wave. This wave mode has the lowest losses on the shield surface and along with that allows to considerably simplify the design of adapters to standard flanges.

5. In terms of design, thin film being part of the waveguide dielectric channel will not be the worst solution for the attachment system intended to attach the dielectric rod inside the shield.

6. With combination of wide-band and narrow-band properties, the resulting waveguide path can be suitable not only for radiometric, but also for interferometric measurements.

7. To reach the set parameters, this path can be made only as a rigid linear waveguide, while rotary devices and adapters require further studies.

8. The presented waveguide path design solution can be implemented in measuring instruments combining both radiometer and interferometer for simultaneous measurement of the distance to and the temperature of the object.

9. This study analyses only possible waveguide path design solutions. Other important elements such as rotary devices, exciters, and wave mode adjusters require further studies.

Bibliography

1. Kostenko A. A. Quasioptics: Historical Preconditions and Modern Trends of Development. Radio Physics and Radio Astronomy. 2000. Vol. 5, No. 3. P. 221–246. (Russian)

2. Vzyatyshev V. F. i dr. Zashchishchenniy dielektricheskiy volnovod s malymi fazovymi iskazheniyami, kod “SHIPR” // Nauchno-tekhnicheskiy otchet. 1998. 126 s. (Russian)

3. Guttzeit E. M. Tipy voln v N-obraznom metallodielektricheskom volnovode // Radiotekhnika i elektronika. 1962. T. 7. No. 2. S. 310–314. (Russian)

4. Krutskikh V. V. Funktsionalnye uzly na poluekranirovannykh dielektricheskikh volnovodakh: dis. … kand. tekhn. nauk. M.: MEI, 2005. 207 s. (Russian)

5. Lebedev I. V. Tekhnika i pribory SVCh. T. 1. M.: Vysshaya shkola, 1970. 440 s. (Russian)

6. Baskakov S. I. Osnovy elektrodinamiki. M.: Sov. radio, 1973. 248 s. (Russian)

7. Vzyatyshev V. F. Dielektricheskie volnovody. M.: Sov. radio, 1970. 217 s. (Russian)

Information about the authors

Krutskikh Vladislav Viktorovich – Cand. Sci. (Engineering), Assoc. Prof., National Research University “Moscow Power Engineering Institute” (MPEI), Moscow, Russian Federation.
Science research interests: radio engineering.

Saadallah Mohamad Minkara – Cand. Sci. (Engineering), Engineer, National Research University “Moscow Power Engineering Institute” (MPEI), Moscow, Russian Federation; Meatel, Beirut, Lebanon.
Science research interests: radio engineering.

Ibrahim Ali Rashid – Cand. Sci. (Engineering), Assoc. Prof., College of Science University of Anbar, Ramadi, Iraq.
Science research interests: radio engineering.

Mirzoyan Artavazd Eduardovich – Postgraduate student, National Research University “Moscow Power Engineering Institute” (MPEI), Moscow, Russian Federation.
Science research interests: radio engineering.

Ushkov Andrey Nikolaevich – student, National Research University “Moscow Power Engineering Institute” (MPEI), Moscow, Russian Federation.
Science research interests: radio engineering.

Металлодиэлектрический экранированный волновод с малыми потерями для диапазона частот 90–100 ГГц

В. В. Крутских[1], М. С. Минкара[1,2], Р. А. Ибрахим[3], А. Э. Мирзоян[1], А. Н. Ушков[1]

[1] Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский университет “МЭИ”», Москва, Российская Федерация

[2] «Митэль», Бейрут, Ливанская Республика

[3] Колледж наук университета Анбара, Рамади, Ирак

Настоящая работа посвящена разработке новой конструкции экранированного металлодиэлектрического волновода с малыми потерями для диапазона частот 90–100 ГГц. Основным препятствием к реализации традиционных волноведущих трактов в данном диапазоне длин волн является высокий уровень потерь в металле. Задачей работы было формирование предложения по конструкции тракта с потерями менее 0,5 дБ/м, с устойчивой поляризацией волны. Для этого были рассмотрены и проанализированы различные конструкции волноведущих структур, проведены оценки погонных потерь в них и возможность реализации конструкции. Была предложена итоговая конструкция волноведущего тракта и выбраны параметры элементов конструкции, отвечающие поставленной задаче.

Ключевые слова: экранированный диэлектрический волновод, малые потери, волновод с малыми потерями, дисперсионная характеристика, инженерный расчет

Об авторах

Крутских Владислав Викторович – кандидат технических наук, доцент кафедры «Основы радиотехники», Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский университет “МЭИ”», Москва, Российская Федерация.
Область научных интересов: радиотехника.

Минкара Мохамад Саадала – кандидат технических наук, инженер кафедры «Основы радиотехники», Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский университет “МЭИ”», Москва, Российская Федерация; «Митэль», Бейрут, Ливанская Республика.
Область научных интересов: радиотехника.

Ибрахим Али Рашид – кандидат технических наук, доцент кафедры «Прикладная математика», колледж наук университета Анбара, Рамади, Республика Ирак.
Область научных интересов: радиотехника.

Мирзоян Артавазд Эдуардович – аспирант кафедры «Основы радиотехники», Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский университет “МЭИ”», Москва, Российская Федерация.
Область научных интересов: радиотехника.

Ушков Андрей Николаевич – студент кафедры «Основы радиотехники», Федеральное государственное бюджетное образовательное учреждение высшего образования «Национальный исследовательский университет “МЭИ”», Москва, Российская Федерация.
Область научных интересов: радиотехника.