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Design of Wideband Waveguide-to-Microstrip Transition for 60 GHz Frequency Band

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Abstract

Introduction. The frequency band around 60 GHz is one of the most promising when it comes to creating new generation communication systems with a high data rate. This is due to the utilisation of a wide operational frequency band that significantly exceeds traditional frequency bands below 6 GHz. The high interest in the development of 60 GHz communication systems is related to the recent evolution of MMIC technology, which allows for the creation of effective components for this band and a variety of planar devices. Both are typically produced on printed circuit boards and have interfaces based on microstrip lines. The wideband waveguide-to-microstrip transition is required for the testing of various active and passive planar devices with microstrip interfaces, in order to provide an effective interconnection between the standard waveguide interface of measurement equipment and planar microstrip structures.

Objective. This paper deals with the design of planar wideband waveguide-to-microstrip transition with low insertion loss level in the 60 GHz frequency band.

Materials and methods. The main objective was achieved by analysing discontinuities in waveguide-to-microstrip transition structure and their influence on transition characteristics. The transition characteristics were analysed using full-wave electromagnetic simulation and confirmed with experimental investigation of designed wideband waveguide-to-microstrip transition samples.

Results. The designed transition was based on an electromagnetic coupling through a slot aperture in a microstrip line ground plane. The transition was performed without the use of blind vias in its structure. This provides for low production cost and allows the integration of the WR-15 rectangular waveguide in a simple manner without any modifications in the waveguide structure. The results of the electromagnetic simulation were confirmed with experimental investigations of the fabricated waveguide-to-microstrip transition samples. The designed transition provides for operation in the nominal bandwidth of the WR-15 waveguide, namely, 50...75 GHz with the insertion loss level of 2 dB and with less than 0.8 dB insertion loss level at the 60 GHz frequency.

Conclusion. The designed waveguide-to-microstrip transition can be considered as an effective solution for interconnection between various waveguide and microstrip millimetre-wave devices due to its wideband performance, low insertion loss level, simple integration and robustness to the manufacturing tolerances structure.

Key words: millimeter wave band; waveguide-to-microstrip transition; printed circuit board; hollow metal waveguide

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ORIGINAL ARTICLE

Широкополосный волноводно-микрополосковый переход для частотного диапазона 60 ГГц

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Аннотация

Введение. Частотный диапазон вблизи 60 ГГц – один из наиболее перспективных для создания высокоскоростных систем связи нового поколения за счет использования широкой полосы частот передаваемых сигналов, существенно превышающей доступные значения до 6 ГГц в традиционных частотных диапазонах. Активное развитие систем связи диапазона около 60 ГГц подкрепляется расширением многообразия соответствующих полупроводниковых компонентов и планарных устройств, реализуемых на СВЧ печатных платах и имеющих интерфейс на основе микрополосковых линий передачи. Для измерения и отладки полупроводниковых компонентов и планарных устройств возникает необходимость их соединения с волноводным интерфейсом измерительного оборудования, что может быть выполнено с помощью волноводно-микрополоскового перехода.

Цель работы. Разработка и исследование планарного широкополосного волноводно-микрополоскового перехода для частотного диапазона около 60 ГГц, обеспечивающего малый уровень вносимых потерь.

Материалы и методы. Для достижения поставленной цели проанализировано влияние неоднородностей в структуре перехода на его характеристики, а также исследованы методы устранения таких неоднородностей. Анализ влияния неоднородностей и расчет характеристик разработанного перехода выполнены с помощью электродинамического моделирования и подтверждены результатами экспериментального исследования изготовленных образцов широкополосного волноводно-микрополоскового перехода.

Результаты. Разработанный переход основан на электромагнитном взаимодействии через щелевую апертуру в экране микрополосковой линии и не содержит в своей структуре слепых переходных отверстий, часто применяемых для переходов миллиметрового диапазона частот, но значительно увеличивающих сложность и стоимость изготовления. Переход выполнен с возможностью непосредственного подсоединения к отрезку прямоугольного волновода стандартного сечения WR-15 без дополнительных модификаций в структуре волновода. По результатам моделирования и экспериментального исследования полоса пропускания перехода равна полной полосе пропускания волновода WR-15, а именно 50...75 ГГц по уровню –2 дБ коэффициента прохождения, а потери, вносимые в передаваемый сигнал, не превышают 0.8 дБ на частоте 60 ГГц.

Заключение. Широкая полоса пропускания сигнала, небольшие потери, устойчивость к неточностям изготовления и простота интеграции позволяют использовать волноводно-микрополосковый переход для соединения различных микрополосковых и волноводных устройств миллиметрового диапазона длин волн.

Ключевые слова: миллиметровый диапазон длин волн, волноводно-микрополосковый переход, печатная плата, металлический волновод

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Introduction. The rapid development of high data rate radio systems arises from the necessity for the wireless transmission of a large amount of information, such as Internet traffic, multimedia and high-definition video streaming. The millimetre-wave band (30…300 GHz) is suitable for the design of such systems, since it allows for the use of a wide frequency bandwidth of up to several gigahertz for signal transmission. This leads to a significant increase in the transmission speed.

The interest among many commercial communication systems developers is focused on the frequency band of about 60 GHz, where new generation Wi-Fi systems [1], radio relay lines for cellular communication systems, fixed wireless access networks operate, and the next fifth generation mobile networks are planned to be deployed [2]. This frequency band includes the oxygen absorption line which determines large values of electromagnetic energy attenuation with a propagation that can be up to 16 dB/km [3]. This significantly limits the possibility of using the frequency band for data transmission over large distances. In this regard, most countries have simplified (or eliminated) licensing procedures for systems and devices in this frequency range and weakened regulatory restrictions [4–6]. Thus, the frequency band near 60 GHz has undergone the greatest growth in the area of communication systems designed to work over short distances of up to 10…20 m indoors and up to 300…500 m outdoors [1, 7].

The great interest in the development of high data rate communication systems in the frequency band near 60 GHz is also supported by the active development and growth of the corresponding semiconductor component base. The various millimetre-wave band devices, including, for example, low-noise amplifiers (LNAs), mixers, filters, and antennas, mainly take the form of planar microstrip structures and utilise technologies such as microwave printed circuit boards, low temperature co-fired ceramics (LTCCs) and semiconductor technologies.

Millimetre-wave measuring equipment usually has a waveguide interface which ensures low transition loss, the ability to transmit high power signals and simple interconnection between the devices under consideration. Planar devices need to be connected to the waveguide interfaces of the measuring equipment for the purposes of their measurement and debugging. Thus waveguide-to-microstrip transition is required for the purposes of transmitting signals from microstrip devices to the waveguide interfaces of the measuring equipment.

This work deals with the design and experimental studies of a planar wideband waveguide-to-microstrip transition for the 60GHz frequency band by using the common high-frequency technology for printed circuit boards manufacturing. The requirements for transition are: low insertion loss level; wide signal bandwidth; and robustness of the manufacturing tolerance structure. A direct connection of the standard WR-15 waveguide needs to be provided for the transition without the need of any modifications in the waveguide structure, which is a typical issue of many similar waveguide-to-microstrip transitions [8–17].

An important issue in the development of waveguide-to-microstrip transition is to ensure a low transition loss level, since the operating frequency increase in the millimetre range can lead to an increase in significant losses in printed structures due to non-uniformity. It is thus important from a scientific point of view to study the influence of irregularities in the transition structure upon its characteristics, as well as to investigate methods allowing the elimination of such non-uniformity.

In order to resolve this issue, the waveguide-to-microstrip transition structure based on an electromagnetic coupling via a slot aperture in the ground plane of the microstrip line has been selected [18–20]. For the purposes of electromagnetic energy concentration in the transition region, metallised vias are used. These connect the waveguide structure along its entire perimeter (except for a small gap at the point of signal input by the microstrip line) with a shielding conductor located at the printed circuit board internal level. This allows for the effective extension of the waveguide in the printed circuit board and arrangement of the radiating element inside the waveguide. It is important to study the influence of the gap in the metallised vias required for signal input by the microstrip line. In order to eliminate the gap influence effect in the vias, consideration is given to the placement in the centre of the microstrip line of an additional hole directly connecting the waveguide and microstrip line ground plane. Two approaches have been studied in this regard. The first of these is based on a blind hole connecting the printed circuit board top layer and the microstrip line ground plane. The second is an original approach based on a through hole which simplifies technological requirements and lowers printed circuit board production cost.

Task formulation. Let us consider main characteristics of the rectangular waveguide and microstrip line.

Hollow metal waveguides are widely used when there is a need to ensure low transition loss level or high-power signals transmission at high frequencies. Rectangular waveguides are used to transmit signals with linear polarisation, and waveguides with circular or square cross sections are used to transmit signals with circular or two orthogonal linear polarisations. Due to size and mass limitations rigid waveguides are usually used at frequencies from 1 GHz to hundreds of gigahertz [21].

All waveguides can be classified by their size which determines their frequency bandwidth. The main classification for rectangular waveguides is given by the International Electrotechnical Commission (IEC) in the corresponding standard [22]. In accordance with this classification, for example, waveguide WR15 has a cross section of 3.75×1.88 mm and it is designed to transmit signals within the frequency range of 50…75 GHz.

The main mode of signal propagation in a rectangular waveguide is the mode TE_{10}, which does not have an electric field component in the signal propagation direction.

The lowest signal propagation frequency of the dominant TE_{10} mode in the WR15 waveguide is 39.97 GHz. The lowest signal propagation frequencies of higher modes have higher values which provide a certain frequency band where only one dominant mode propagates. The closest mode for the WR15 waveguide is TE_{20}, which propagates at frequencies above 80 GHz. Thus, the passband of the WR15 waveguide can be considered equal to 40…80 GHz. However, in order to ensure the best signal transmission, the standard recommends using the WR15 waveguide for signals with the frequency band of 50…75 GHz.

The microstrip line is a planar structure consisting of a central conductor separated from the conductive screen by a dielectric substrate. The microstrip line is easy to manufacture by using printed circuit board technology which has a low mass production cost. Its disadvantages in comparison with a rectangular waveguide include limitation of a transmitted signal power and a higher level of losses. Many publications have reported on the analytical study of the microstrip line, for example, [20].

The dominant mode in microstrip transmission lines is a quasi-TEM mode. It differs from the TEM mode, which has no longitudinal components of both electric and magnetic fields, in that this line is not symmetrical. Only part of the electric field is concentrated in the substrate between the microstrip and ground plane, while the rest of the electric field is concentrated next to the microstrip in the air. This leads to differences in the field structure in the air (dielectric constant $\varepsilon = 1$) and in the substrate ($\varepsilon > 1$). This results in the appearance of the longitudinal components of the electric field, which become more noticeable as the frequency increases.

The electric and magnetic field structures of the rectangular waveguide and microstrip line possess significant similarities which allow for the possibility of the development of a waveguide-to-microstrip transition in a wide frequency range.

Literature describes a wide variety of waveguide-to-microstrip transitions, in particular, transitions using a conductor placed inside the waveguide [8–11], or a matching metal ridge [12], and transitions based on electromagnetic coupling through a slot aperture in the waveguide [13, 14]. However, such transitions are poorly adapted for operation in the millimetre-wave band, since they require modifications in the waveguide structure that must be performed with very high accuracy. This leads to a significant manufacturing cost increase and installation difficulties.

The most promising transitions in the millimetre-wave band are waveguide-to-microstrip transitions with electromagnetic (non-contact) coupling through a slot aperture in the microstrip line ground plane [18, 19]. This type of transition does not require modifications in the waveguide structure and provide simple interconnection of planar devices and robustness to manufacturing inaccuracies.

Waveguide-to-microstrip transitions with electromagnetic coupling through a slot aperture in the ground plane of the microstrip line are designed to operate at a frequency of 60 GHz and often perform on a ceramic substrate by using LTCC (Low Temperature Co-fired Ceramics) technology due to its high manufacturing accuracy, wide technological capabilities, and low losses. However, this technology leads to a significantly higher production cost and manufacturing time in comparison with standard high-frequency technologies for the manufacturing of printed circuit boards. The possibility of using standard materials for high data rate printed circuit boards in the development of waveguide-to-microstrip transitions of the millimetre-wave band is shown in [19]. However, the transition reported in [19] has a limited passband (11.5% with respect to the centre frequency of 60 GHz) and a significant loss level (about 2 dB at 60 GHz). Moreover, blind metallised vias are used in the waveguide-to-microstrip transition structure presented in [18]. This fact significantly increases the manufacturing cost and is accompanied by technological limitations.

This paper presents the design of a wideband waveguide-to-microstrip transition with low losses at a frequency of 60 GHz by using standard printed circuit board manufacturing technology. The development is carried out by using the full-wave electromagnetic simulation and experimental study of transition test structure.

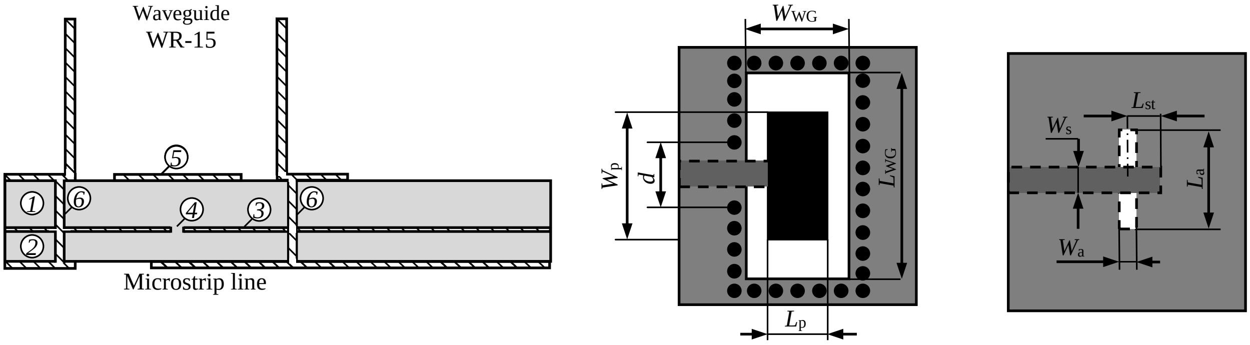
Results of the full-wave simulation of the waveguide-to-microstrip transition. The thus-designed waveguide-to-microstrip transition structure is shown in Fig. 1, where *a* is the cross-section, *b* is the top view, and *c* is the bottom view. Microwave material RO4003C by "Rogers" with a dielectric constant of $\varepsilon = 3.54$ at a frequency of 60 GHz is used as a dielectric substrate [23]. The loss tangent value of $\mathrm{tg}\,\delta = 0.0058$ is set in accordance with the experimental data presented in [24].

The structure under consideration has three metallisation layers separated by the dielectric substrate. This includes two layers *1, 2* of the microwave material RO4003C with a thickness of 0.2 mm each and a binder prepreg RO4450B by "Rogers" with a thickness of 0.2 mm. The inner metallisation layer *3* is a continuous ground plane layer. A waveguide segment is located on one side and on the other a microstrip line. The signal transmission from the waveguide to the microstrip line is through the slot aperture *4* in the ground plate by using the radiating patch *5* on the upper metallisation layer, allowing for better transition in a wide frequency band. The total thickness of this printed circuit board is 0.66 mm, and the thickness of each metallisation layer is 18 μm. The structure of electric fields in the designed waveguide-to-microstrip transition is shown in Fig. 2.

Several stacked radiating elements are often used to increase the waveguide-to-microstrip transition passband [16]. Analysis has revealed that with the appropriate choice of transition parameters, a single radiating patch can be used to provide a transition passband equal to the entire bandwidth of the waveguide.

The use of metallised vias (Fig. 1, *b*) connecting the waveguide along its entire perimeter (except for a small gap where a signal is fed by the microstrip line) with a ground plane allows for the effective extension of the waveguide and the positioning of the radiating element inside. This also fulfils a restriction on the absence of modifications in the standard waveguide for this transition. The distance between adjacent vias has a great influence on waveguide-to-microstrip transition characteristics [15] For this reason, it is made as small as possible within technological limitations. Through vias with a diameter of 0.18 mm and a distance between adjacent vias of 0.2 mm are used. Since it is not possible to produce e vias with the given parameters at the place of signal input by the microstrip line, a certain gap occurs.

Blind holes between two upper layers of metallisation can be used to avoid a gap in the vias where a signal is fed by the microstrip line [15, 16]. However, this leads to difficulties in manufacturing technology



a *b* *c*

Fig. 1. The waveguide-to-microstrip transition structure: a – cross-section; b – top view; c – bottom view

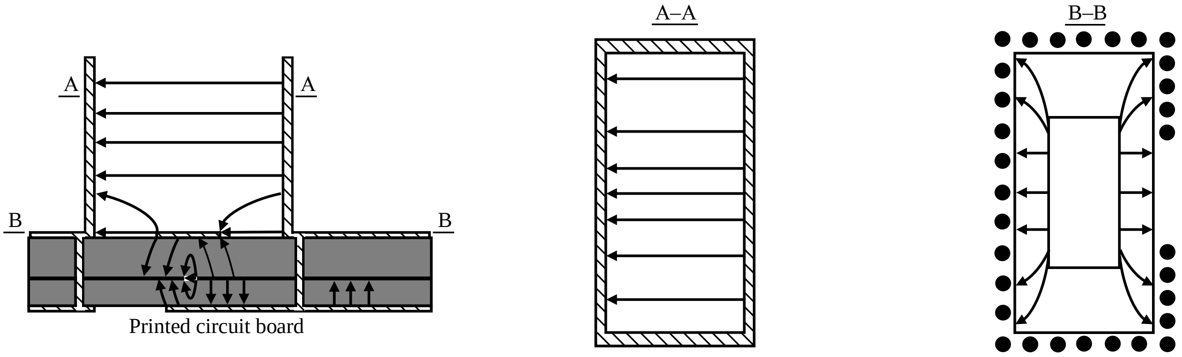


Fig. 2. The electric fields distribution in the waveguide-to-microstrip transition

and a consequent increase in production costs. This article presents the results of studying the effect of the gap between through holes located near the microstrip line on waveguide-to-microstrip transition characteristics.

3D electromagnetic simulation of the designed waveguide-to-microstrip transition structure is performed using CST Microwave Studio. The effect of the gap in vias where a signal is fed by the microstrip line within the range of the gap size *d* of 0.8…1.4 mm on the transition characteristics is studied. The frequency dependencies of transmission S_{21} and reflection S_{11} coefficients obtained as a result of this simulation are shown in Fig. 3.

The simulation results show that when the vias are located around the waveguide entire perimeter with a small gap between the vias, then the microstrip-to-waveguide transition provides a passband equal to the waveguide entire bandwidth. However, given the presence of a significant (more than 1 mm) gap between the vias, there is a dip in the transmission coefficient in the passband. As the gap between the vias increases, the dip increases in depth and shifts toward the lower frequencies. When performing electromagnetic simulation, it was found that as the gap in the vias increases, the level of side radiation increases and electromagnetic energy concentration on the inner layers of the printed board also increases. This explains the presence of the dip in the waveguide-to-microstrip transition transmission coefficient. The models of the electric field density in the transition cross section for the gap in the vias of *d* = 0.8 and 1.4 mm are shown in Fig. 4.

The study proposes a wave-guide-to-microstrip transition design that allows the gap in vias to be avoided without increasing the transition complexity. The method considers placing an additional through hole directly in the centre of the microstrip line. This would necessitate a sufficiently large line width $(W_\text{S} > 0.4 \text{ мм})$, compatible with the 50-Ohm microstrip line width on the selected structure of the printed circuit board. In this case, vias can be placed around the entire waveguide perimeter. At the same time, a round border without metallisation would be required around the through hole located in the microstrip line centre in order to prevent the microstrip line from short circuiting to the ground plane. This structure forms the microstrip line irregularity which

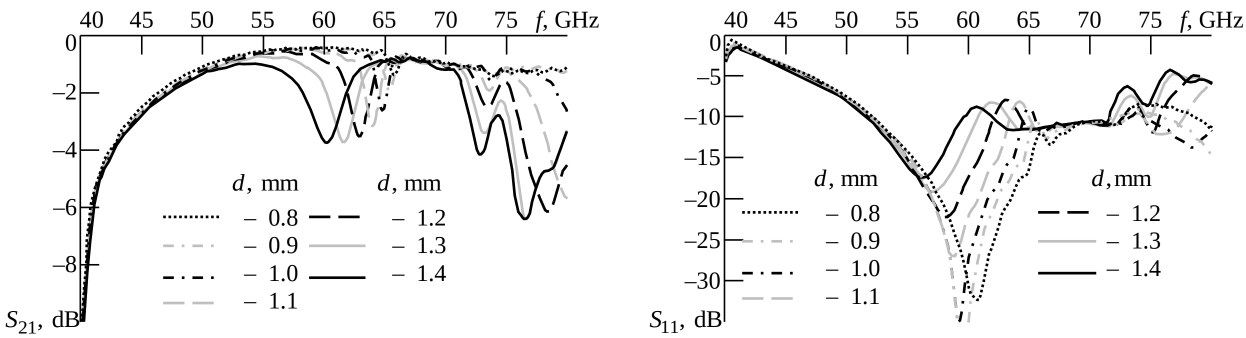
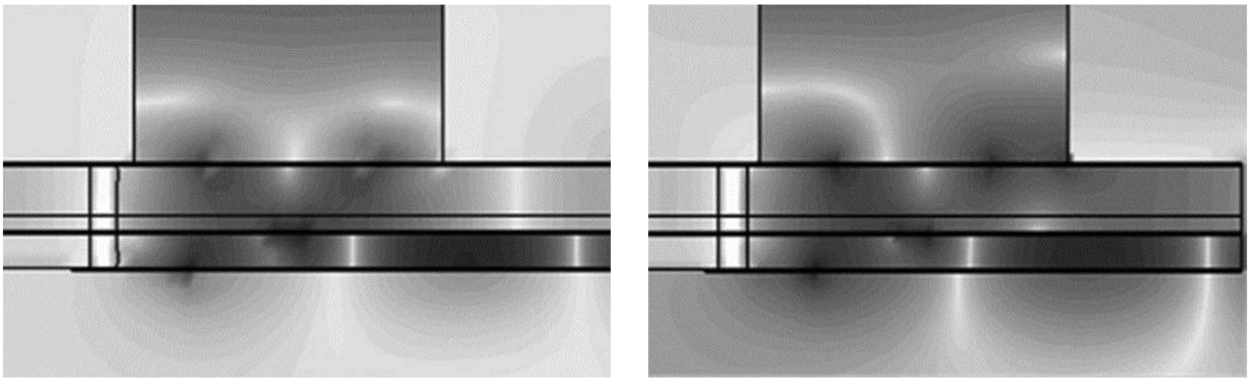


Fig. 3. Frequency dependences of transmission S_{21} and reflection S_{11} coefficients



$d = 0.8$ mm $d = 1.4$ mm

Fig. 4. Models of the electric field density in the transition cross section

can be compensated by widening the microstrip line part located directly under the waveguide.

The final structure of the designed waveguide-to-microstrip transition with an additional through hole in the centre of the microstrip line is shown in Fig. 5. The dimensions of the transition elements (see Fig. 1) are $W_{\mathrm{WG}} = 1.88$ mm, $L_{\mathrm{WG}} = 3.76$ mm, $W_{\mathrm{p}} = 2$ mm, $L_{\mathrm{p}} = 0.93$ mm, $W_{\mathrm{s}} = 0.45$ mm, $W_{\mathrm{a}} = 0.18$ mm, $L_{\mathrm{a}} = 1.8$ mm, $L_{\mathrm{st}} = 0.6$ mm. The microstrip line widening $W_{\mathrm{m}} = 0.9$ μm is made to compensate the effect of the through hole.

Fig. 6 shows the simulation results of reflection and transmission coefficients of the waveguide-to-microstrip transition with an additional through hole in the microstrip line centre (lines *1*). For comparison, Fig. 6 shows the simulation results for a waveguide-to-microstrip transition with a structure based on a blind hole connecting the upper metallisation layer to the microstrip line ground plane on its inner metallisation layer (lines *2*). The simulation results show that the transition thus designed provides a signal transmission from the waveguide to the microstrip line in the entire waveguide passband. This ensures smooth change of the transmission coefficient due to the presence of vias around the entire waveguide perimeter. The transition thus designed possesses characteristics close to the characteristics of a blind hole transition thus confirming the effectiveness of the proposed design. Transition losses are less than 0.5 dB at the centre frequency of 60 GHz, and the passband at the level of –1 dB of the transmission coefficient which is more than 15 GHz (or more than 25% of the centre 60 GHz frequency). Over the entire waveguide bandwidth (50…75 GHz), a signal is transmitted with losses not exceeding 2 dB.

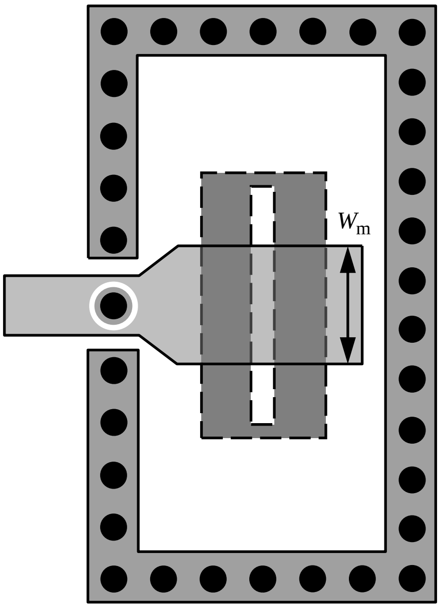


Fig. 5. The structure of the designed waveguide-to-microstrip transition with an additional hole

An additional simulation with modified dimensions of conductors and gaps between them was carried out in order to assess the effect of manufacturing inaccuracies on the characteristics of the designed transition. The maximum deviations values of the conductors and gap width in the simulation were equal to ± 10% as provided for in standard production technology of printed circuit boards.

The electromagnetic simulation results for various combinations of deviation values for the individual transition elements are shown in grey in Fig. 7. The black line represents the initial simulation results. The simulation results show that the deviation of the individual transition element sizes produces a

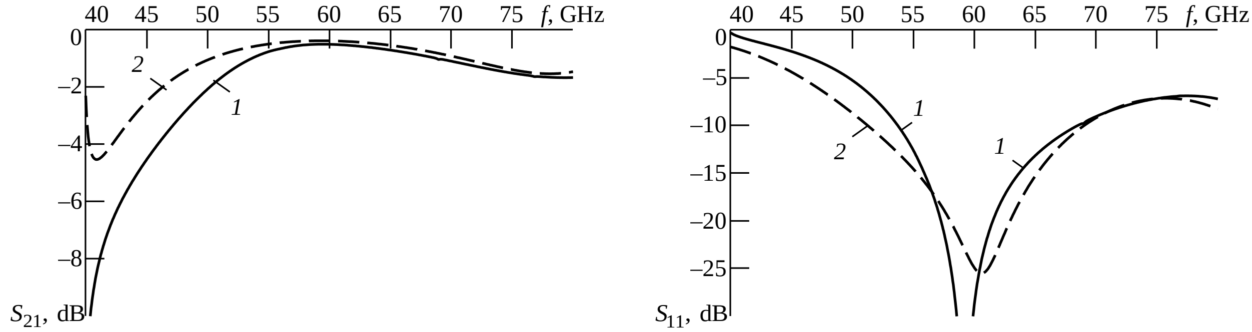


Fig. 6. Frequency dependences of reflection and transmission coefficients of a waveguide-to-microstrip transition with an additional hole: *1* – through hole; *2* – blind hole

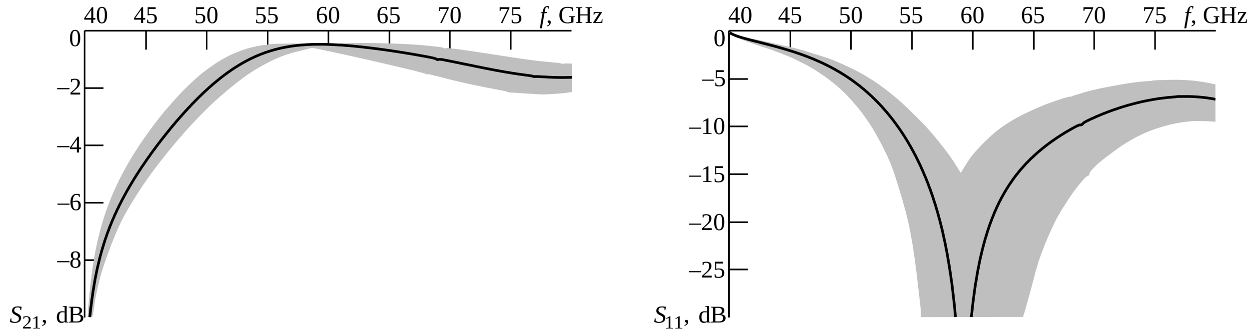


Fig. 7. The influence of manufacturing inaccuracies on the waveguide-to-microstrip transition characteristics: gray region belongs to a range of characteristics with 10 % inaccuracy; black line shows simulation results without inaccuracies

small shift in the operating frequency band. In this case, transmission coefficients vary within no more than 0.4 dB from the initial value. It should be noted that in the most cases, manufactured printed circuit boards have smaller size deviations. This ensures good repeatability of the transition characteristics over the entire operating frequency band.

Experimental studies. For the purposes of experimental investigations into the designed waveguide-to-microstrip transition, a back-to-back transition "waveguide – microstrip line – waveguide" was manufactured with an additional through hole in the centre of the microstrip line. A photograph of the manufactured printed circuit board with the back-to-back transition is shown in Fig. 8.

The RO4003C by "Rogers" printed circuit board microwave material referred to above was used as a substrate to ensure a significantly lower manufacturing cost than the LTCC technology traditionally used in the millimetre-wave range. The size of the printed circuit board is 50×20 mm. The distance between the two waveguide-to-microstrip transitions is equal to 30 mm to ensure convenient connection of the waveguides with diameters of about 20 mm. It should be noted that the transition loss in the microstrip line with a conductor of 0.45 mm width and 30 mm length is 2.5…3 dB.

Measurements of the back-to-back waveguide-to-microstrip transition were carried out by using a Gunn diode oscillator tunable in a frequency range of

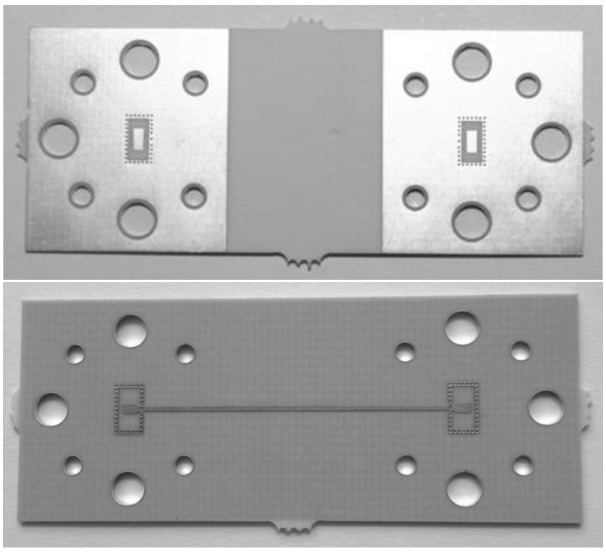


Fig. 8. Model of a printed circuit board with a double sided transition "waveguide–microstrip line–waveguide"

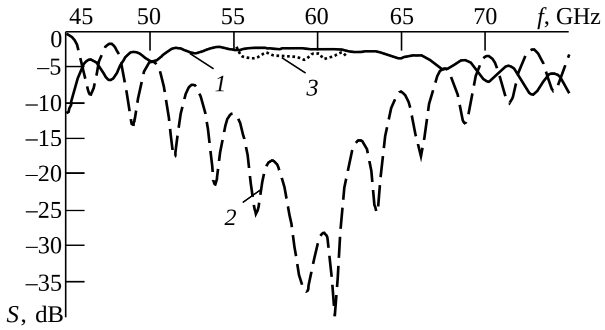


Fig. 9. Simulation and measurement results of the double sided transition "waveguide–microstrip line–waveguide" characteristics: *1* – S_{21}, simulation; *2* – S_{11}, simulation; *3* – S_{21}, measurements

55…62 GHz with a waveguide output interface. The transmitted signal is received and analysed by an Agilent E4407B spectrum analyser together with an external Agilent 11970V down-mixer. Measurements and back-to-back transition samples are set by prepositioned and fixed laboratory equipment, allowing for the minimising of mechanical effects (flexions, torsions, and etc.) on the printed board, thereby improving the repeatability of the measured characteristics. Special holes are made in the printed board to allow its positioning by using pins of the standard waveguide flange UG-385/U. This also reduces displacements of the waveguide structure relative to the printed circuit board.

The electromagnetic simulation results of frequency dependences of the transmission coefficient S_{21} (line *1*) and reflection coefficient S_{11} (line *2*), as well as measured values of the transmission coefficient S_{21} of the back-to-back transition "waveguide–microstrip line–waveguide" (line *3*) are shown in Fig. 9.

The measurement results show that the attenuation in the waveguide-to-microstrip transition passband corresponds well to simulation results and is on average 4…4.5 dB (according to the simulation results 3.5 dB). Thus, taking losses in the microstrip line into account, losses in one waveguide-to-microstrip transition are not more than 0.8 dB. The difference in measurement results is about 1 dB and is due to manufacturing inaccuracies. The measurements of several printed circuit boards samples show consistent results, thus proving the stability of the designed transition to manufacturing inaccuracies.

Conclusion. The paper presents the results of the design and study of the planar wideband waveguide-to-microstrip transition for the frequency band of 50…75 GHz. The waveguide-to-microstrip transition is based on the coupling of electromagnetic fields in the waveguide and microstrip line through the slot aperture in the microstrip line ground plane. The standard high-frequency technology for printed circuit boards production is used to ensure low manufacturing cost compared to LTCC technology. The additional through hole in the microstrip line centre provides for a passband produced by the designed transition equal to the entire bandwidth of the waveguide WR-15.

Experimental studies were performed on the back-to-back transition "waveguide–microstrip line–waveguide". Measurements of the transition characteristics supported the electromagnetic simulation results. Experimental investigations into several manufactured samples of the designed transitions show a good level of robustness of the transition with regard to manufacturing inaccuracies. As seen from the results obtained, the transition bandwidth is 25 GHz (more than 40%) at the level of –2 dB of transmission coefficient, and the losses are no more than 0.8 dB at the central frequency of 60 GHz.

The study shows that the implementation of an additional through hole in the microstrip line centre allows for the elimination of non-regularity in the transition structure and ensures a low level of losses in the waveguide-to-microstrip transition in the frequency range of 50…75 GHz. The approach presented in this paper allows all the requirements implied on the transition thus designed to be satisfied. The wide signal bandwidth, low loss level, robustness to manufacturing inaccuracies and integration simplicity, allow for the use of the waveguide-to-microstrip transition for interconnection between various microstrip and waveguide millimetre-wave devices.

Authors' contributions

Andrey V. Mozharovskiy **–** the study of ways to eliminate the influence of irregularities in the transition structure. Development of a transition design with the blind hole that eliminate the influence of irregularities. Full-wave simulation of the developed transition structures. Preparation of the paper text.

***Aleksei A. Artemenko* –** development of the design of the transition with a through hole in the center of the microstrip line. Carrying out measurements of manufactured samples of back-to-back transition structures.

***Roman O. Maslennikov* –** management of the work.

***Irina B. Vendik* –** management of the work. Preparation of the paper text.

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