Cost-Effective Implementation of Air-Filled Waveguides on Printed Circuit Boards

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***Abstract*— This paper presents a new cost-effective method to produce air-filled waveguides out of a printed circuit board (PCB) with a milling machine and how to implement them with standard PCB technology. For this purpose, low cost substrates like FR-4 are used. For the baseboard to waveguide transition in the E-Band (60 - 90 GHz) a WR12 waveguide connector [1] was used. The WR12 waveguide was manufactured and analyzed on mechanical deviations. The RF performance in the E-Band was measured and compared to common PCB waveguides like microstrip lines (MS) and grounded coplanar waveguides (GCPW).**

Keywords—low loss transmission lines, air-filled waveguide, submount, WR12, PCB

I. Introduction

Millimeter wave systems nowadays have to deal with high data rates and continuously increasing integration density. Besides the steady progressing miniaturization in electronics industry, low fabrication costs and high quality are required simultaneously. Moreover, for millimeter wave applications low loss transmission lines are a key technology. In [2], a GCPW with reduced attenuation by partially removed substrate was analyzed. The measurement showed an improved attenuation of 0.25 dB/cm at 90 GHz. Another technology of great interest for many practical applications in standard low cost PCB manufacturing processes is the substrate integrated waveguide (SIW), because of its robustness against production tolerances [3]. With regard to quality factor and losses, these devices are a good compromise between the performance of planar circuits and classical waveguides. However, conventional rectangular waveguides are often preferred, due to the low insertion loss as they are completely filled with air (dielectric constant $DK_{air} \approx 1$ and dissipation factor $DF_{air} \approx 0$). Therefore, high research effort is taken to implement waveguides on PCBs to combine the benefits of the SIW and the classical rectangular waveguide. Devices like the air-filled substrate integrated waveguide (AFSIW) already showed, that passive structures (e.g. waveguides or filters) produced in AFSIW technology have a better RF performance than the conventional SIW ([4] - [5]). In [4] and [5] the AFSIW was realized as planar structure, analyzed and compared to conventional SIWs up to 60 GHz. Whereas in this paper, the air-filled waveguides are realized in submount technology and their RF performance were analyzed in the full E-Band. A great advantage of using waveguides as submounts is the fact that the necessary manufacturing techniques are available in conventional circuit board technology. In addition, the submounts can be fully assembled in SMD production lines due to their smooth surface.

II. Air-Filled Waveguides

A. *Manufacturing of Submount Waveguides*

Producing a waveguide as a submount allows the use of cost effective substrates (e.g. FR-4) as they also can be used for the production of the baseboard. For this purpose, a cavity depth milling technology was used to create the waveguide structures. Subsequently, the structures were coated with copper (25 µm) and silver (250 nm), to create a conductive surface. The produced WR12 waveguide submounts are shown in Fig. 1. The milling machine has to deal with composed materials in a multilayer PCB (consisting of different substrates and prepregs), which have various physical, thermal and mechanical properties. Furthermore, the end of a milling cutter normally has different sharp edges. Those sharp edges and high process dynamics usually lead to work piece vibrations. Therefore, locally different cutting forces affect the processed surface, leading to variable surface qualities (see Chapter II B). Fig. 2 shows a close-up view of the produced waveguide. The notches and scratches on the surface are caused by an inappropriate milling strategy and by worn milling cutters. This causes mechanical deviations which will also influence the RF properties. Milling processes have to be optimized individually, depending on which PCB materials and cutters are involved.

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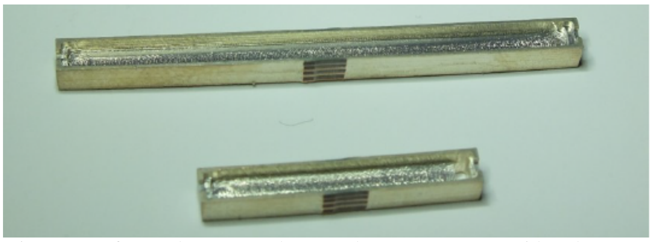

Fig. 1 Manufactured 22 mm and 44 mm long WR12 waveguide submounts

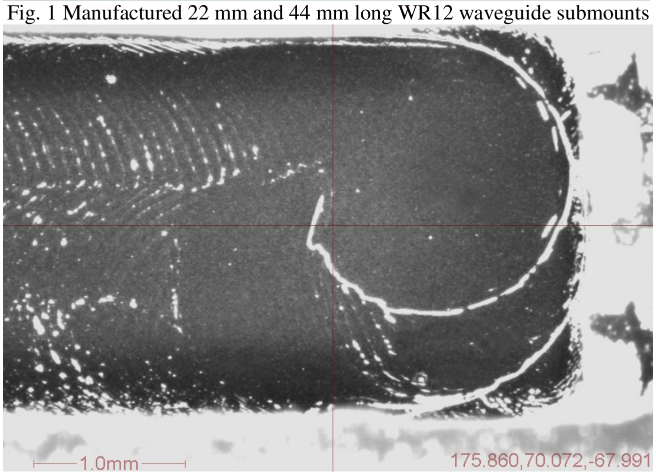

Fig. 2 Irregularities on the surface of the WR12 waveguide submount

B. *Influence of Mechanical Deviations*

As the quality of the inner surfaces is affected by nearly every parameter of the milling process and the used substrate materials, roughness may vary at every surface. Especially the copper roughness of the different waveguide walls has big influence on the RF properties in the upper two-digit GHz range. Both signal phase delay and attenuation are significantly increased, when dealing with rough surfaces in the millimeter wave range [6]. Therefore, it is important to fabricate the inner walls of the waveguide as smooth as possible. The area based RMS roughness S_q of the waveguide was deduced with a laser scanning microscope. Each surface was measured five times and then averaged. Fig. 3 shows a cutout of three different waveguide surfaces.

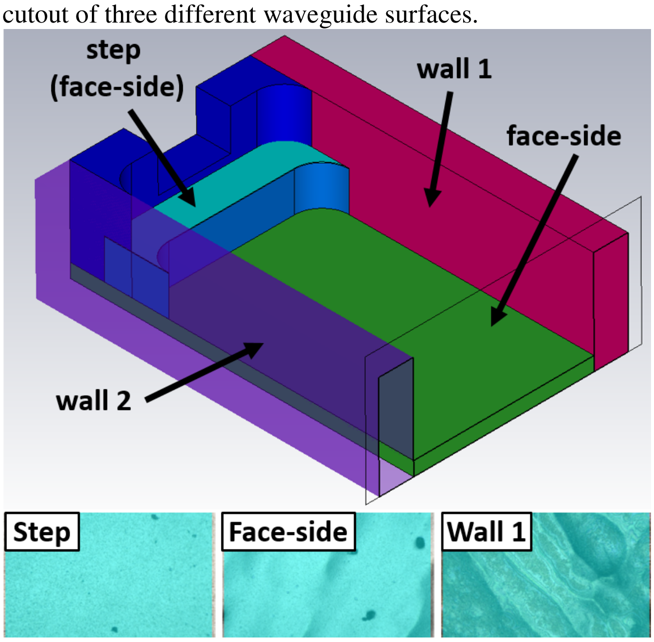

Fig. 3 Model of the waveguide and laser scanning microscope images of the different surfaces

It has been found that $S_{q,wall\ 1}$=2.77 µm, $S_{q,wall\ 2}$=1.67 µm, $S_{q,step}$=0.19 µm and $S_{q,face\text{-}side}$=1.15 µm. The roughness of the baseboard copper was considered with the values denoted in [2]. Two different milling cutters were used for the step and the face-side, leading to different $S_{q,step}$ and $S_{q,face\text{-}side}$ values. For the face-side a worn milling cutter was used, and a new one for the step. Therefore, the use of worn milling cutters should be avoided. Furthermore, the roughness of the two walls varies by about 1.1 µm. This is due to the different cavity milling processes (parallel and reverse milling). It has been found, that reverse milling (used for Wall 1) causes rougher surfaces than parallel milling (used for Wall 2). Besides the copper roughness, the manufacturing deviation (±50 µm) of the used cavity milling machine also influences the quality of the transition from the WR12 connector to the WR12 waveguide submount. Table 1 shows the mechanical dimensions of the produced WR12 waveguide.

Table 1 Mechanical dimensions of the WR12 waveguide

Mechanical deviation	**WR12 waveguide 22 mm**	
	Target value (mm)	***Measured (mm)***
a (waveguide width)	3.10	3.12
b (waveguide height)	1.52	1.53
Total length	22	22
Step length	0.9	0.87
Step depth	1	1.01

Deviations in the dimensions of the step (length/depth) lead to worse impedance matching and decreased quality of the transition. Also the dimensions (height (b) and width (a)) of the waveguide submount can be affected. The conductor losses of a waveguide can be calculated as [7]:

$$\alpha_C = \frac{R_S}{b \cdot \frac{\mu_0}{\varepsilon_0}} \cdot \frac{\left(1 + \frac{2b}{a} \cdot \frac{\omega_c^2}{\omega^2}\right)}{\sqrt{1 - \frac{\omega_c^2}{\omega^2}}} \qquad (1)$$

With R_S denoting the surface resistance, ω_c the angular cutoff frequency, μ_0 the permeability constant and ε_0 the permittivity constant. At maximal deviation of a and b (-50 µm), the insertion loss is increased by about 0.18 dB/m at 75 GHz and, therefore, has less impact on the attenuation. Additionally, very precise milling is necessary for the step.

III. Design and Measurement

For the measurement of the air-filled waveguide submounts a WR12 waveguide connector [1] was used. The PCB waveguide transitions was designed and analyzed with the 3D EM field simulator CST Microwave Studio®. This has been done with a WR12 rectangular waveguide connector as described in [1].

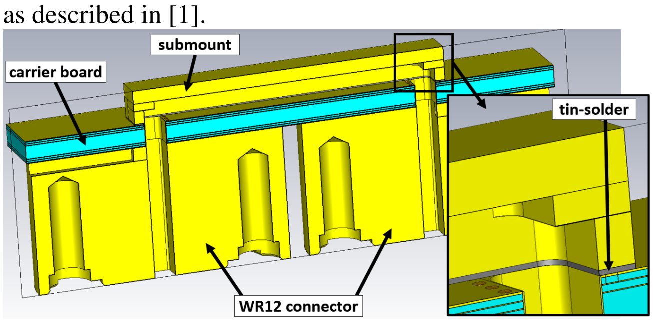

Fig. 4 WR12 waveguide connector to WR12 waveguide submount transition

The WR12 waveguide connector can easily be attached on the backside of the baseboard. For this purpose, an additional milling process is necessary to connect the WR12 connector with the waveguide submount. To eliminate parasitic propagation of the electric field into the substrate material of the baseboard, the milled hole was coated with copper through electroplating (Fig. 4). The corresponding simulation and measurement results are illustrated in Fig. 5. The measurement of the 22 mm long waveguide submount has an insertion loss of 0.45 – 1.36 dB in the full E-Band (60 – 90 GHz).

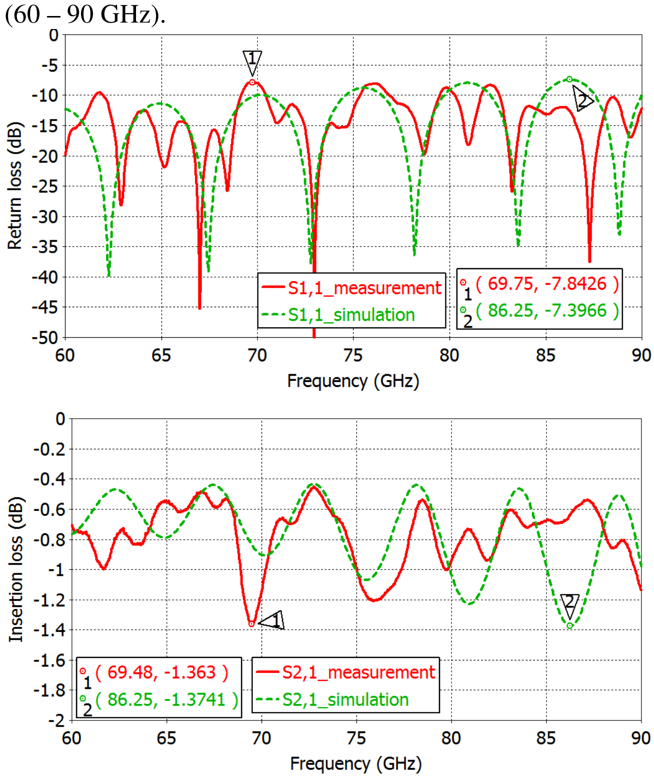

Fig. 5 Simulation and measurement of the WR12 connector to WR12 waveguide submount transition

Due to mechanical deviations, the waveguide has slightly larger dimensions than the WR12 standard. This decreases the attenuation of the measurement compared to the simulation.

IV. Potential of Air-Filled Waveguides on PCBs

In order to show the great potential of an air-filled waveguide in terms of insertion loss, a WR12 waveguide with 1 m length was measured directly with WR12 connectors. To get a compact design, the delay line was realized spiral-shaped which can easily be implemented on PCBs. Fig. 6 shows the delay line soldered onto the baseboard and the corresponding X-ray picture for evaluating the mechanical quality of the waveguide. Fig. 7 compares the insertion loss of the air-filled waveguide to common waveguides on PCBs. In contrast to MS and GCPW the attenuation of the WR12 waveguide is improved by 73 dB and 53 dB at 75 GHz, respectively (Fig. 7).

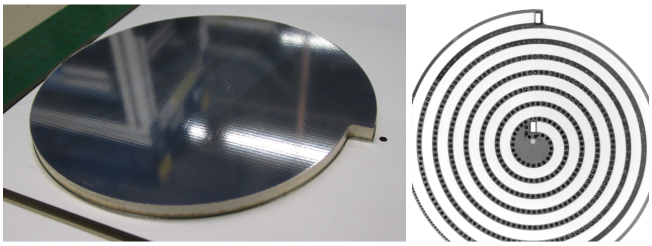

Fig. 6 Mounted WR12 delay line (left) and corresponding X-ray view (right)

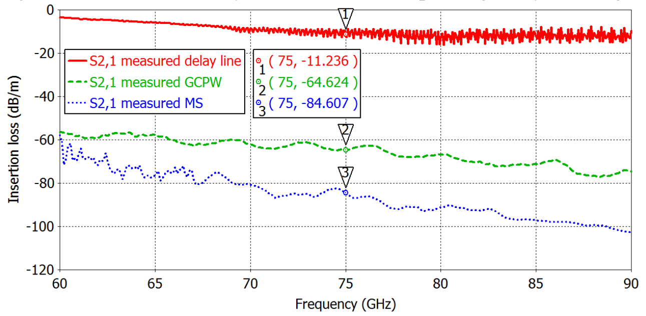

Fig. 7 Comparison between common waveguides (MS and GCPW with 5 mil substrate: DF=0.0015) and an air-filled WR12 waveguide

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