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

Kevin Kunze[#1],
Franz Xaver Röhrl[#~2], Stefan Zorn[#~3]

[#]THD Technische Hochschule Deggendorf, Dieter-Görlitz-Platz 1, 94469 Deggendorf, Germany

[~]Rohde & Schwarz GmbH & Co. KG, Werk Teisnach, Kaikenrieder Straße 27, 94244 Teisnach, Germany

[1]kevin.kunze@stud.th-deg.de,
{[2]franz.roehrl, [3]stefan.zorn}@rohde-schwarz.com

***Abstract* — This paper presents a new cost-effective method for the production of air filled SIWs (AFSIW) in conventional printed circuit board (PCB) substrates with a CO2 Laser and how they can be implemented with standard PCB technology. For this purpose, submounts with low cost substrates like FR-4 are used. First, a transition from baseboard to waveguide is realized in the E-Band (60 - 90 GHz) with a quarter wavelength line as impedance transformer. Then an iris window bandpass is designed for a passband from 44 to 54 GHz. The RF performance in the E-Band is compared to common PCB waveguides like microstrip lines (MS), grounded coplanar waveguides (GCPW) and substrate integrated waveguides (SIW).**

Keywords — low loss transmission lines, air filled waveguide, air filled SIW, AFSIW, submount, iris window bandpass filter, WR12, WR19, printed circuit board, PCB

I. Introduction

Millimeter wave systems must handle with high data rates and constantly increasing integration density. In addition to the steadily increasing miniaturization in the electronics industry, low manufacturing costs and high quality are required at the same time. For millimeter wave applications, a low-loss signal transmission is of high importance. In [1] the substrate was partially removed in a GCPW in order to minimize attenuation by an increased field guidance in air. The measurement showed an improved attenuation of 0.25 dB/cm at 90 GHz, compared to a GCPW without removed substrate. Furthermore, the substrate integrated waveguide (SIW) has many practical applications, since it is manufactured entirely with low-cost standard PCB technology and has a high robustness against manufacturing tolerances [2]. In terms of 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, because of their low insertion loss, as they are completely filled with air (dielectric constant $DK_{air} \approx 1$ and dissipation factor $DF_{air} \approx 0$). To combine the advantages of the SIW and the classical rectangular waveguide, high research efforts is made to implement waveguides on PCBs. In [3] and [4] an air-filled substrate integrated waveguide (AFSIW) was presented and it was shown that passive structures (e.g. waveguides or filters) in AFSIW technology have a better RF performance than the conventional SIW. The AFSIW was realized as a planar structure on the inner layer of a multilayer PCB, analyzed and compared with conventional SIW up to 60 GHz ([3] - [4]). Whereas in this paper, the air-filled SIWs are realized in submount technology. This allows the structures to be realized on the outer layer and therefore no additional transition to the inner layer is necessary for signal feeding. A great advantage of using submount AFSIWs is the fact that the necessary manufacturing techniques are available in conventional printed circuit board technology. In addition, the submounts can be completely assembled in SMD production lines due to their smooth surface. This leads to a very flexible and cost efficient implementation of the AFSIW technology.

II. Desgin of AFSIW with Submounts

For the production of air filled substrate integrated waveguides a 127 µm (5 mil) low loss substrate material (Taconic TSM-DS3) is used for the base board and cost-effective FR-4 for the submount. To feed a signal into the waveguide, a suitable transition must be designed. This transition should be suitable for a frequency range of 60 to 90 GHz (WR 12). In addition, an iris window bandpass is implemented for a WR19 waveguide in the frequency range from 44 to 54 GHz. The different structures are designed and analyzed with the 3D-EM field simulator CST Microwave Studio®.

A. *Manufacturing of Submount Waveguides*

In the production of submount AFSIWs, a series of vias is first placed as a lateral boundary of the waveguide. Then the printed circuit board is structured in the etching process. In contrast to the production of a SIW, the upper copper layer is replaced by the copper layer of the submount. An annular ring of 150 µm must remain around the lateral vias. With a CO2 laser, as used in the production of microvias in PCB technology, the substrate can be removed by stringing together several closely spaced laser holes. A PCB with removed substrate for a WR12 submount AFSIW is shown in Fig. 1.

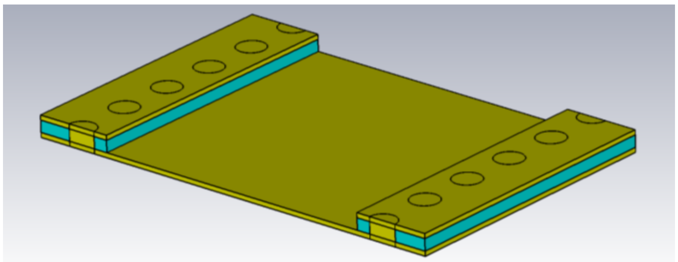

Fig. 1 PCB with removed substrate for a WR12 submount AFSIW

This step results in an increased field component in air in the subsequent waveguide. This method has already been used successfully in [1] to minimize the attenuation of MS and GCPW. In the area of the vias and the surrounding annular ring, the upper copper layer cannot be removed without destroying the via metallization. The underlying substrate can therefore not be removed with the laser. A conductive upper boundary is required to replace the etched upper copper layer. This is achieved by automatic assembly (via pick & place) of a metallized submount, as shown in Fig. 2.

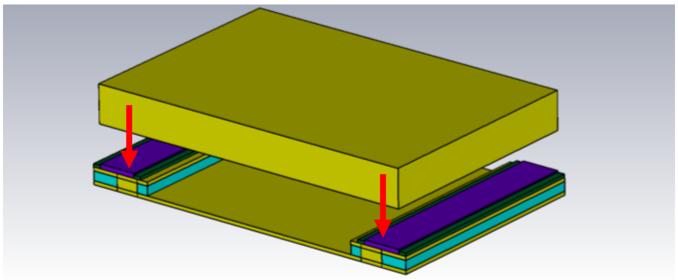

Fig. 2 PCB when assembling the submount

With the help of the lateral vias, the lower copper layer and the submount, a waveguide is created that is mostly filled with air (Fig. 3).

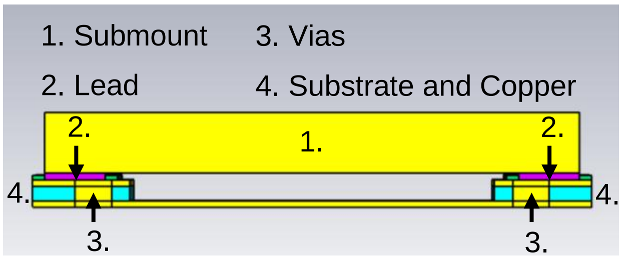

Fig. 3 Air Filled Submount AFSIW (cross sectional view)

The submounts can be separated from a base board with a panel milling machine. Cost-effective substrates (e.g. FR-4) can be used for this purpose.

A. *GCPW to WR12 AFSIW Transition*

To convert the coplanar mode to TE10 waveguide mode, a quarter wavelength line is used as impedance transformer. This principle is already known from signal coupling into a SIW [5]. The model of the WR12 transition is shown in Fig. 4.

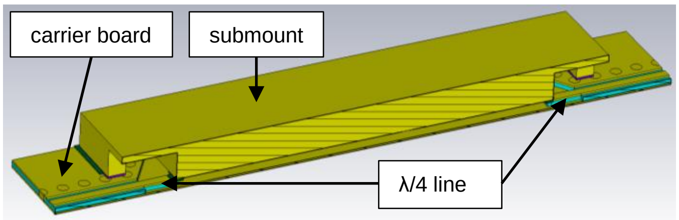

Fig. 4 Simulation model of the WR 12 transition

Since quarter wavelength lines are susceptible to radiating power, the submount is modified to have a shielding effect (Fig. 5).

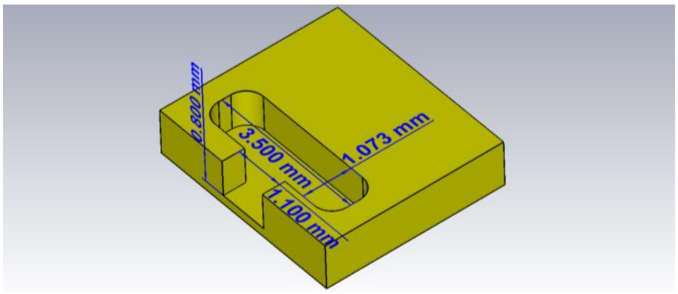

Fig. 5: Submount as shielding (bottom view)

For this purpose, cavity depth milling technology is used to manufacture the structures. Since the interior of the submount consists of substrate material, a conductive surface must be created. The submount is therefore coated with copper (25 µm) and silver (250 nm) by electroplating. Fig. 6 shows the simulation model of the WR 12 transition with (a) and without the shielding (b).

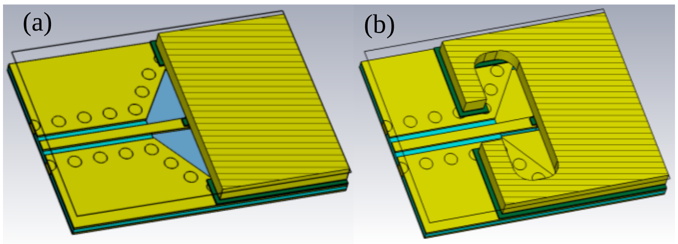

Fig. 6 Simulation model of the WR 12 transition with shielding (a) and without shielding (b)

The transition to WR 12 Submount AFSIW is optimized in the whole U-Band (60 - 90 GHz). The simulation results are shown in Fig. 7. Geometry modifications of the transition and the waveguide allow the adjustment of the usable frequency range.

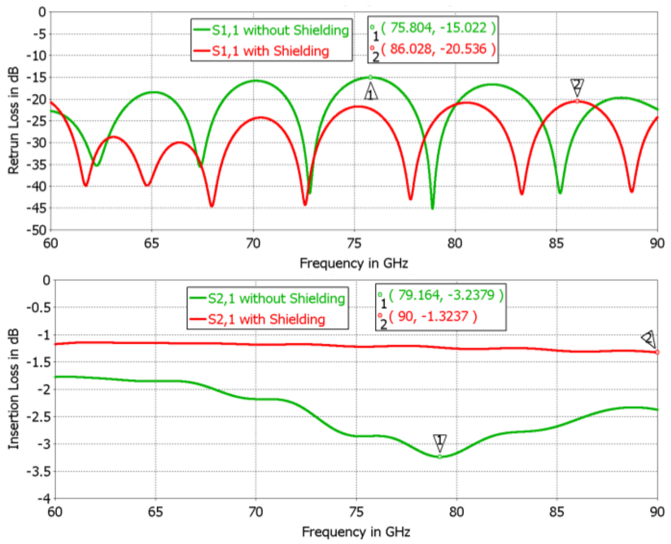

Fig. 7 Simulation results of the transition to WR 12 submount AFSIW

In the simulation of the submount AFSIW (length 22 mm), the shielding results in an improvement of the insertion loss in the entire E-band from 3.2 dB to 1.3 dB. This can be attributed to the reduced radiation. With the shielding a return loss of better 20.5 dB can be achieved, without only 15.0 dB.

B. WR19 Iris Window Bandpass Filter

A WR19 9th order iris window bandpass filter with a passband in the frequency range from 44 to 54 GHz is realized. The principle of the signal feed-in is identical to that in chapter A. For the filter characteristics iris windows are inserted into the waveguide (Fig. 8).

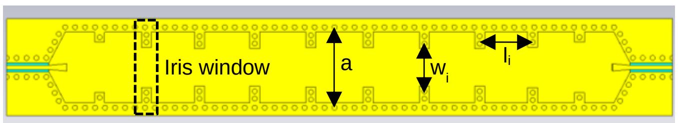

Fig. 8 WR19 Iris Window Bandpass Filter without submount

The iris windows are defined in the etching process of the upper copper layer and additional vias are inserted. For this purpose, only low cost PCB technology is used, and no further milling process is necessary. Geometry modifications of the parameters a, w_i and l_i allow the adjustment of the usable frequency range.

Fig. 9: Cross section through iris window (Fig. 8, dashed line)

The submount is soldered to the iris windows, resulting in a lateral metallic boundary over the entire height of the waveguide (Fig. 9). The corresponding simulation results are illustrated in Fig. 10.

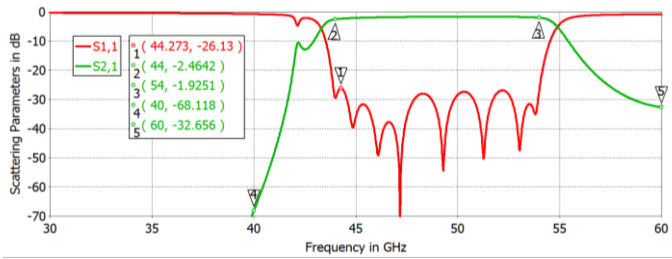

Fig. 10 Simulation results of the WR19 iris windows bandpass filter

In the simulation of the iris window bandpass filter, an insertion loss of better than 2.5 dB and a return loss of at least 26.1 dB in the entire passband can be obtained. An attenuation of 68.1 dB at 40 GHz is achieved in the lower stopband and 32.7 dB at 60 GHz in the upper stopband.

III. Potential of Air Filled Waveguides on PCBs

To demonstrate the great potential of an air-filled waveguide in terms of insertion loss, the WR12 submount AFSIW from Fig. 6 (b) is compared with conventional PCB waveguides like microstrip lines (MS), grounded coplanar waveguides (GCPW) and substrate integrated waveguides (SIW) (Fig. 11). For a good comparability, all structures have the same length of 10 cm.

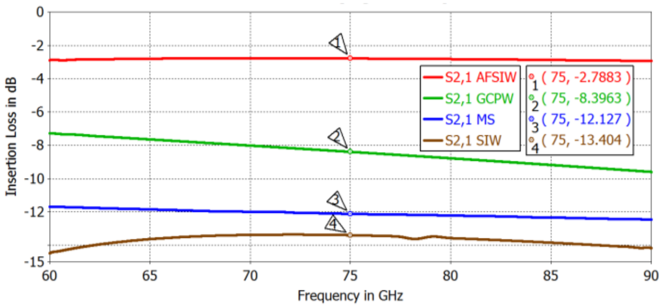

Fig. 11 Comparison between common waveguides (MS, GCPW and SIW with 5 mil substrate: DF=0.0015) and a WR12 submount AFSIW (length = 10 cm)

The AFSIW has an insertion loss of 2.8 dB at 75 GHz, which is 11.7 dB less than the value of a conventional SIW (Fig. 11). In contrast to MS and GCPW, the attenuation of the AFSIW is improved by 5.6 dB and 9.3 dB at 75 GHz.

IV. Conclusion

In this paper, the potential of air filled waveguides is shown. AFSIWs realized in submount technology can be manufactured and implemented on PCBs using standard technology. In addition, the submounts can be fully assembled in SMD production lines due to their smooth surface on top side. This makes the waveguide submounts very cost efficient. Since the base materials of the carrier board and the submount both consist of circuit board material, the submounts can also be relatively large due to the little CTE (coefficient of thermal expansion) mismatch. A broadband transition to the introduced PCB waveguide and an iris window bandpass has been designed. The insertion loss of the submount AFSIW is very low (2.8 dB per 10 cm @ 75 GHz) compared to conventional PCB waveguides (MS: 12.1 dB per 10 cm @ 75 GHz).

Acknowledgement

The Project PaGAnIni is financially supported by the Bavarian Ministry of Economic Affairs, Regional Development and Energy. All kinds of support are gratefully acknowledged. The authors also like to thank Rohde & Schwarz Teisnach for all the fabrication and measurement support.

References

[1] F. Sepaintner, A. Scharl, F. X. Rohrl, W. Bogner, and S. Z. Zorn, "Simulation and Manufacturing of Low Loss PCB Structures with Additional Electromagnetic Field in Air," in *2019 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, Bochum, Germany, Jul. 2019, pp. 94–96, doi: 10.1109/IMWS-AMP.2019.8880079.

[2] F. X. Röhrl *et al.*, "Cost-effective SIW band-pass filters for millimeter wave applications a method to combine low tolerances and low prices on standard pcb substrates," in *2017 47th European Microwave Conference (EuMC)*, Nuremberg, Germany, Oct. 2017, pp. 416–419, doi: 10.23919/EuMC.2017.8230878.

[3] F. Parment, A. Ghiotto, T.-P. Vuong, J.-M. Duchamp, and K. Wu, "Air-filled SIW transmission line and phase shifter for high-performance and low-cost U-Band integrated circuits and systems," in *Global Symposium on Millimeter-Waves (GSMM)*, Montreal, QC, Canada, May 2015, pp. 1–3, doi: 10.1109/GSMM.2015.7175444.

[4] A. Ghiotto, F. Parment, T. Martin, T. P. Vuong, and K. Wu, "Air-filled substrate integrated waveguide — A flexible and low loss technological platform," in *2017 13th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*, Nis, Oct. 2017, pp. 147–149, doi: 10.1109/TELSKS.2017.8246250.

[5] E. Miralles, H. Esteban, C. Bachiller, A. Belenguer, and V. E. Boria, "Improvement for the design equations for tapered Microstrip-to-Substrate Integrated Waveguide transitions," in *2011 International Conference on Electromagnetics in Advanced Applications*, Torino, Italy, Sep. 2011, pp. 652–655, doi: 10.1109/ICEAA.2011.6046418.