Packaged Cost-Effective Millimeterwave Air-Filled SIW Components for Array Feed Networks

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***Abstract*—In this contribution, we investigate the implementation of air-filled substrate-integrated-waveguide (AFSIW) components based on the assembly of multiple standard manufactured single printed circuit boards (PCBs) as a cost-effective, low loss routing alternative for millimeterwave antenna arrays. To this end, a transition from grounded co-planar waveguide (GCPW) to AFSIW is designed, fabricated and measured for integration purposes with active electronics in the n257 5G band. The measured minimal insertion loss equals 0.7 dB around 27 GHz. To further validate our approach, a compact, fully shielded AFSIW filter, including the aforementioned transition, is designed and prototyped. It is shown that the component radiates less than 5% of its power, eliminating most of the spurious radiation from feed networks.**

***Index Terms*—5G, air-filled substrate-integrated-waveguide (AFSIW), grounded co-planar waveguide (GCPW), filter, millimeterwave (mmWave), standard PCB manufacturing, transition**

I. Introduction

Each generation of communication technology brings forth a new era of applications, all requiring different sets of hardware, integrated in the same device. The stringent data requirements trigger an evolution towards higher frequencies to accommodate bandwidth hungry applications, inevitably calling for antenna arrays to overcome the larger path loss. Therefore, packaging becomes increasingly important for the intricate routing networks of antenna arrays to avoid electromagnetic interference (EMI)/ electromagnetic compatibility (EMC) problems. Power loss of these growing feed networks is another important aspect, promoting the use of low loss air-filled substrate-integated-waveguide (AFSIW) technology [1].

Integration of monolithic microwave integrated circuits (MMICs) raises new challenges, especially in terms of interfacing with AFSIW. A low loss, efficient transition from AFSIW to a planar transmission line (TML), e.g. grounded co-planar waveguide (GCPW), is essential to this end [2]. While the ease of integration is crucial in fully functional systems, minimizing the cost is equally important. Therefore, we propose a fabrication technology based on assembled single standard printed circuit board (PCB) manufactured layers [3].

In this paper, we investigate the implementation of AFSIW components based on the advocated fabrication technology as a cost-effective, low-loss routing alternative for millimeterwave antenna arrays. In Section II, we elaborate on the proposed stack-up, while Section III analyzes the design, fabrication and measurements of a transition from GCPW to AFSIW around $27\,\mathrm{GHz}$. Subsequently, this transition is used for the characterization of a compact, fully shielded, AFSIW dual-cavity circular filter operating in half of the n257 5G band (26.5-$29.5\,\mathrm{GHz}$), accommodating the uplink communication. The measured performance of the aforementioned components is summarized in the conclusion Section V.

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II. Proposed Stack-up

We propose packaged routing of antenna array feed networks to avoid any EMI/EMC issues. To this end, five separate PCBs are manufactured using standard fabrication technology to minimize the cost. The proposed stack, shown in Fig. 1, is solderlessly assembled by using pins in the foreseen alignment holes of the prototypes. Two AFSIW layers are implemented to accommodate highly efficient routing.

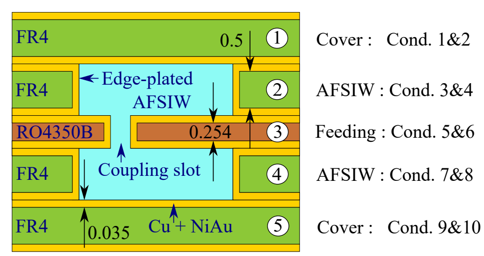

Fig. 1. Proposed PCB stack for packaged millimeterwave components.

Two PCBs (1 and 5) are used as covers to eliminate most radiation from the routing network. Another two PCBs (2 and 4) are employed for the low loss, milled and edge-plated AFSIW components. In our proposed solution, milled features have a minimal bending radius (depending on the commercial PCB service, in our case $0.25\,\mathrm{mm}$), since milling does not permit $90°$ corners. All four aforementioned PCBs may be integrated on any desired laminate. However, since no electromagnetic fields penetrate the dielectric material, we have opted for a low-cost $0.5\,\mathrm{mm}$-thick FR4 laminate to optimize overall cost-effectiveness. The third, central layer 3, is implemented on a $0.254\,\mathrm{mm}$-thick RO4350B laminate, which is used as a GCPW routing layer for measurement purposes or integrated circuit (IC) interconnection.

III. Interface Transition

A transition from AFSIW to a planar TML, such as GCPW, is indispensable to route signals towards antenna elements, measurement equipment or ICs [1]. We have designed, fabricated and measured such a GCPW-to-AFSIW transition, depicted in Fig. 2, for optimal operation in the frequency band ranging from 26.5 GHz to 27.5 GHz, including a guard band at each side. A cross-shaped cover, implemented in AFSIW-layer ② according to the proposed stack-up in Fig. 1, is included to shield the normally radiating patch with stub structure of conductor 5 (Cond. 5), to ensure maximal power transfer through the coupling slot on conductor 6 (Cond. 6) into the AFSIW on PCB ④. A custom-defined TRL calibration kit is used to de-embed up to the port planes in Fig. 2.

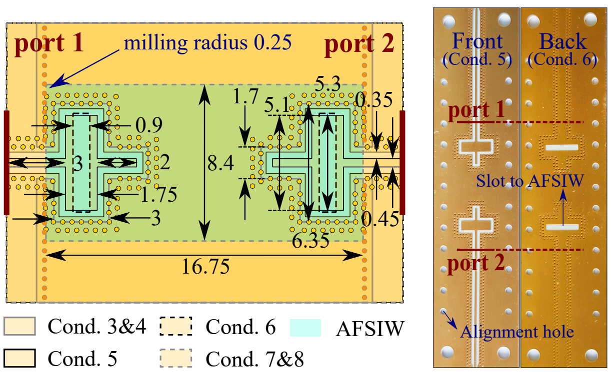

Fig. 2. (left) Layout of the GCPW-to-AFSIW transition with indicated dimensions in millimeter, and (right) fabricated prototype feeding layer ③ of the GCPW-to-AFSIW transition.

The scattering parameters of this transition, shown in Fig. 3, indicate good agreement between measurement and simulation, albeit marginally shifted in frequency. The minimal insertion loss of 1.4 dB observed in measurement, which is 0.7 dB per transition, is only slightly higher than the simulated value of 0.7 dB. The maximal additional insertion loss of the proposed back-to-back transition remains below 3 dB in the frequency range from 24.5 GHz to 27.5 GHz in measurement, and from 24.6 GHz to 28.5 GHz in simulation. When including the electroless nickel immersion gold (ENIG) surface finish in the simulation, where the nickel layer is 5 μm and the gold layer is 0.1 μm thick, an excellent agreement (Fig. 3, dotted) with the measurements is observed, indicating the adverse effect of the ferromagnetic nickel material when the gold layer is thinner than the skin depth.

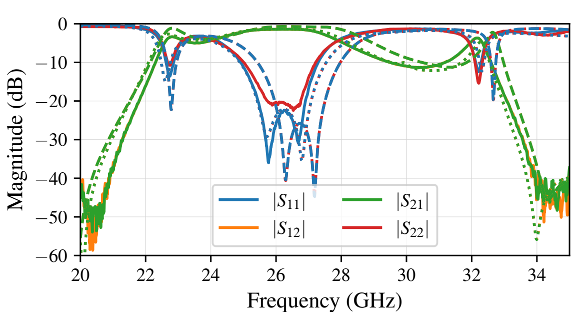

Fig. 3. S-parameters of the GCPW-to-AFSIW transition: measured (solid), simulated without NiAu finish (dashed), and with NiAu finish (dotted).

To further investigate this effect, we have examined the losses for this transition. The simulated in-band power loss (including radiation, dielectric and conductor loss for a surface roughness (SR) of 300 nm) amounts to 17% when ignoring the NiAu surface finish, while the measured loss adds up to an acceptable 30%. Thus, this transition performs very well and provides an excellent shielded interface to AFSIW components.

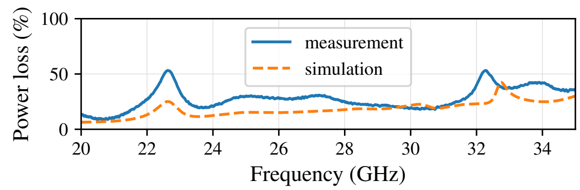

Fig. 4. Power loss of the GCPW to AFSIW transition : $1 - |S_{11}|^2 - |S_{12}|^2$.

IV. AFSIW Dual-cavity Filter

Filters are essential components in communication systems, since they reduce the noise and suppress spurious signals of out-of-band frequencies. We have designed a compact AFSIW-based dual-cavity circular filter to operate from 26.5 GHz to 27.5 GHz on the same PCB stack as shown in Fig. 1. The multi-layer filter topology, introduced in Fig. 5, allows a compact implementation of the filter by folding the planar design over its symmetry axis. The fabricated prototype in parts is shown in Fig. 6, excluding the top cover ① for clarity. The entire design, including both transitions, is smaller than $2\lambda_{0,28\mathrm{GHz}} \times 2\lambda_{0,28\mathrm{GHz}}$. A steep roll-off is introduced at the right side of the operating band to exclude spurious signals from the rest of the n257 band [4].

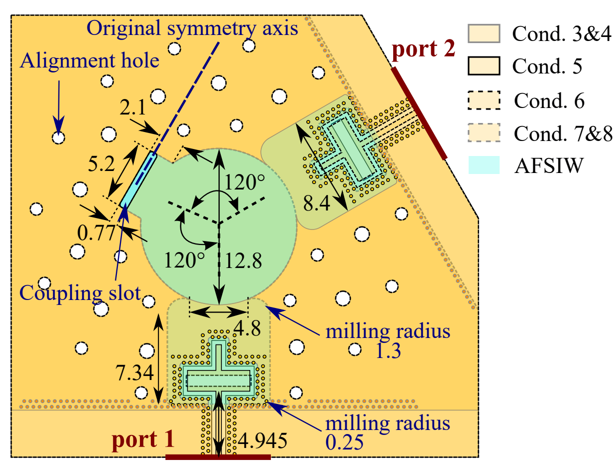

Fig. 5. Layout of the filter, including the proposed GCPW-to-AFSIW transition, with indicated dimensions in millimeter.

This filter is based on the TE_{10}-mode traveling through the AFSIW, which has a cut-off frequency at 17.4 GHz for a waveguide width of 8.4 mm. The attenuation pole is provided by the TM_{110}-resonance of the circular cavity, theoretically located at 28.5 GHz for a cavity radius of 6.4 mm. The

AFSIW-implemented filter is extended with our proposed transition to GCPW of Figs. 5 and 6. Incoming GCPW feed lines are implemented on opposite sides of the same high frequency laminate, as shown in Fig. 6, leveraging efficient PCB usage, according to the proposed stack of Fig. 1.

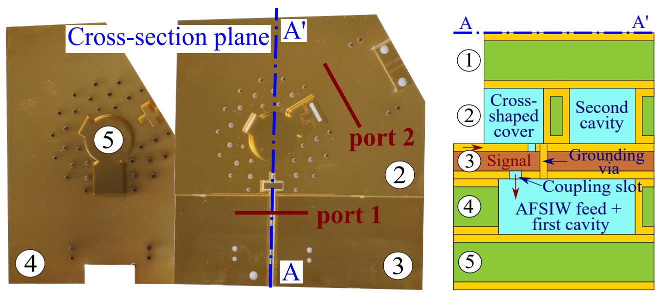

Fig. 6. Unassembled fabricated filter prototype parts according to the stack-up in Fig. 1, except cover 1, including cross-section AA' for clarity.

In Fig. 7, the simulation excluding the surface finish (dashed line), exhibits a minimal insertion loss of 1 dB, while the measurements (solid line) show a 5.2 dB loss. The measured 3 dB-bandwidth covers 25.6 GHz to 27.3 GHz, whereas the original simulation ranged from 25.9 GHz to 27.8 GHz. A more accurate simulation model including the NiAu surface finish (dotted line) shows excellent agreement with the measurements.

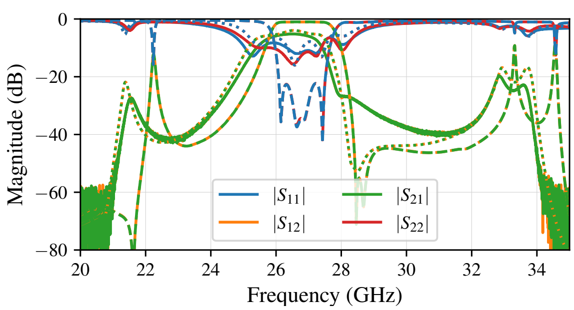

Fig. 7. Scattering parameters of the proposed filter: measured (solid), simulation without NiAu finish (dashed), and with NiAu surface finish (dotted).

A thorough analysis of each loss aspect is represented in Fig. 8. The radiated power loss is less than 5%, clearly demonstrating that our design and manufacturing strategy meets the goal of mitigating EMI/EMC issues. Dielectric loss adds 7.5% power loss for the GCPW and its transition towards the AFSIW, while the conductor loss is around 10%. An SR of 300 nm increases the loss in the passband by another 5%. The most substantial loss factor is proven to be the ENIG surface finish (5 μm-thick Ni and 0.1 μm-thick Au), since it causes around 30% of the power loss in the passband of this filter.

The good agreement between the simulation including the ENIG finish and the measurements, validates the performance of the proposed filter. Employing an alternative surface finish [5] could further improve the filter topology implemented in our advocated technology as an attractive solution for non-radiating, low-loss feed networks for millimeterwave antenna

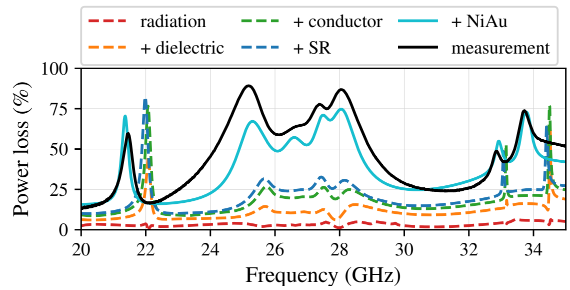

Fig. 8. Power loss for each loss mechanism in case of the proposed filter.

arrays. Interfacing active electronics is straightforward thanks to the AFSIW-to-GCPW transition, while integration towards a multitude of antenna designs is equally undemanding. Topologies employing AFSIW may be interfaced directly to the AFSIW output of the filter, while GCPW or other planar TMLs may employ the proposed transition. Additional cavities may be added to the proposed design when increased roll-off on both sides of the passband are necessary for the envisaged application. However, this comes at the cost of an increase in insertion loss and an increased amount of PCB layers.

V. Conclusion

In this paper, we presented a cost-effective, fully shielded fabrication process, based on stacking multiple single-layer printed circuit boards (PCBs) in standard manufacturing technology. The proposed stack includes two layers for low-loss air-filled substrate-integrated-waveguide (AFSIW) routing towards antenna arrays. To this end, a transition from grounded co-planar waveguide (GCPW) to AFSIW is designed, manufactured and measured around 27 GHz, exhibiting a minimal insertion loss of 0.7 dB per transition. Finally, we have proposed a novel compact folded AFSIW dual-cavity circular filter operating from 26.5 GHz to 27.5 GHz employing the aforementioned transition, which radiates less than 5% of its power. The designed filter including two transitions fits within a footprint smaller than $2\lambda_{0,28\mathrm{GHz}} \times 2\lambda_{0,28\mathrm{GHz}}$. During the conference, a diplexer will be shown in the proposed, fully shielded technology.

References

[1] K. Wu, M. Bozzi and N. J. G. Fonseca, “Substrate integrated transmission lines: review and applications,” IEEE Journal of Microwaves, vol. 1, no. 1, pp. 345–363, winter 2021.

[2] J.-C. Henrion et al. “Multilayer GCPW-to-AFSIW transition for high-performance systems on substrate,” IEEE Microwave and Wireless Components Letters, vol. 32, no. 6, pp. 676–679, June 2022.

[3] L. Van Messem et al. “A 4x4 millimeterwave-frequency Butler matrix in grounded co-planar waveguide technology for compact integration with 5G antenna arrays,” IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 1, pp. 122–134, June 2022.

[4] H. J. Tang, W. Hong, J.-X. Chen, G. Q. Luo and K. Wu, “Development of millimeter-wave planar diplexers based on complementary characters of dual-mode substrate integrated waveguide filters with circular and elliptic cavities,” IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 4, pp. 776–782, Apr. 2007.

[5] A. Ippich, “PCB Surface Finish Impact to Losses at High Frequencies,” IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS), pp. 1–4, Nov. 2019.