Substrate Integrated Coaxial Line Millimeterwave Components Manufactured in Standard PCB

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***Abstract*—We propose a packaging technique for the intricate routing networks in millimeterwave (mmWave) applications based on substrate integrated coaxial lines (SICLs), to eliminate spurious feed network radiation that may influence the antenna array's radiation pattern. Next to a thorough comparison with grounded co-planar waveguides (GCPWs), a coaxial via transition and a novel packaged hybrid coupler are designed, fabricated and measured in the 28 GHz 5G bands. The proposed shielded coaxial via transition from SICL to SICL exhibits a measured insertion loss smaller than 0.7 dB from 24 GHz to 30 GHz, while the measured amplitude imbalance of the hybrid coupler remains below 1 dB and the phase imbalance does not exceed 6°.**

***Index Terms*—5G, grounded co-planar waveguide (GCPW), hybrid coupler, millimeterwave (mmWave), packaged, standard PCB manufacturing, substrate integrated coax line (SICL)**

I. Introduction

More and more devices are added to the elaborate wireless network each day, promoting omni-present interconnectivity. Inevitably, all emerging new applications must be integrated into these devices, but they require diverse sets of hardware. Therefore, inter-component and intra-component electromagnetic interference (EMI)/ electromagnetic compatibility (EMC) considerations become increasingly important to ensure reliable functionality. Especially when moving to higher frequencies, where antenna arrays are necessary to overcome the increased path loss, extensive routing networks are essential, but these may generate a significant amount of spurious radiation that influences the radiation pattern. Questions arise on how to compactly package this multitude of subsystems.

Generally, grounded co-planar waveguide (GCPW) is favored as a compact option with reduced radiation characteristics for high-performance implementations [1]. The combination of GCPW and stripline technology generates a compact, low loss, easily integratable substrate integrated coaxial line (SICL) with good power handling capabilities [2]. Since it is the planar version of a coaxial line, excellent shielding is provided, presenting an attractive solution for packaged systems. Popular fabrication techniques for SICL employ multi-layered printed circuit boards (PCBs) to implement their components. However, this is a costly and time-consuming process.

In this paper, we propose an assembly of multiple single-layer PCBs, fabricated with standard manufacturing technology and locally soldering signal lines to obtain a galvanic contact, to significantly reduce the cost, while not compromising the shielding nor increasing undesired spurious radiation. We have designed, fabricated and measured several essential components for beamsteering and routing networks to validate our advocated solution. In Section II, we discuss the proposed fabrication technology in depth. Consequently, this section performs an elaborate comparison between GCPW and SICL transmission line technology to position the SICL-performance with respect to the state of the art. Section III first proposes a transition from SICL to SICL as an alternative to the 3D-GCPW transition of [3]. Our design is analyzed and compared to measurements. Next, a novel hybrid coupler implemented in SICL technology, including a transition from SICL to GCPW for measurement purposes, is presented. In Section IV, the conclusion summarizes the measured performance of all aforementioned components.

II. Packaging Technique

To avoid EMI/EMC problems, the development of reliable millimeterwave (mmWave) systems requires careful packaging of components that may generate undesired radiation. In this respect, this section demonstrates the main advantages of the proposed packaging technique. By using simulations and measurements, an analysis is performed for operating frequencies from $24\,\mathrm{GHz}$ to $30\,\mathrm{GHz}$, thus including the following 5G bands: the n257 band (26.5-$29.5\,\mathrm{GHz}$), the n258 band (24.25-$27.5\,\mathrm{GHz}$), and the n261 band (27.5-$28.35\,\mathrm{GHz}$).

A. Fabrication Technology

We propose using multiple assembled single-layer PCBs manufactured through standard fabrication. This allows a cost-effective design. A $0.254\,\mathrm{mm}$-thick RO4350B high-frequency laminate is employed with $35\,\mu\mathrm{m}$-thick conductor layers including an electroless nickel immersion gold (ENIG) surface finish. Packaging passive components by using our advocated SICL transmission line technology avoids EMI/EMC problems by eliminating radiation, while maintaining all the advantages of GCPW technology. The technology exhibits good power handling capabilities, while maintaining a small footprint. Since the fields are concentrated around the signal conductor, radiation and crosstalk between adjacent lines are minimized. Compared to their GCPW variants, an additional advantage of the SICL technology, introduced by the increased effective relative permittivity, is the miniaturization of all components.

The construction of the SICL is explained in Fig. 1. It consists of traditional GCPW signal line with groundplanes added next to them, connected to the bottom ground conductor

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by rows of vias, spaced at 0.5 mm to suppress field leakage in the frequency range under consideration [4]. Another PCB, with the same grounding structures, but without the signal conductor, is then added on top of the GCPW-PCB. Our proposed packaged solution avoids undesired radiation. The assembly of both PCBs results in a total thickness of 0.648 mm.

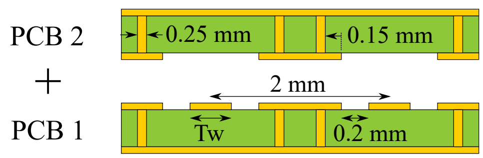

Fig. 1. Cross-section of two parallel GCPW lines, consisting solely of PCB 1, with a trace width (Tw) of 0.41 mm, and, two completely shielded SICL lines, by assembling PCB 1 and PCB 2, where Tw = 0.285 mm.

B. GCPW Compared to SICL

The advantages of the proposed packaging solution are highlighted by comparing the traditional GCPW with SICL transmission lines. To this end, two adjacent 3 cm-long lines are spaced 2 mm apart. The GCPW is matched to 50 Ω by employing a trace width (Tw) of 0.41 mm, while the SICL requires a trace width of only Tw = 0.285 mm for matching, owing to its increased effective relative permittivity. Both lines have a fixed gap width of 0.2 mm between the signal conductor and the ground planes next to it. All ground patterns are connected to the bottom ground plane by vias of diameter 0.25 mm, spaced at 0.25 mm from each other and 0.15 mm from the copper edge. The simulation model of Fig. 1 yields the scattering parameters shown in Fig. 2. The SICL exhibits an overall improved performance in terms of near-end crosstalk (NEXT) and far-end crosstalk (FEXT).

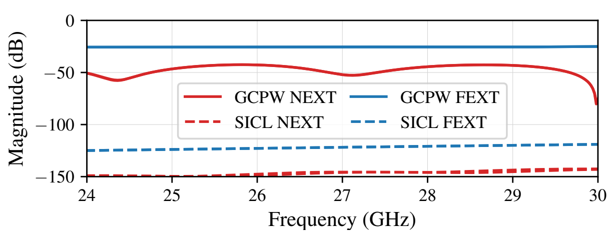

Fig. 2. Comparison of parallel GCPW (solid) and SICL (dashed) lines with 2 mm separation, both of which have comparable insertion loss (0.4-1 dB) and reflection coefficients below −25 dB from 24 GHz to 30 GHz.

Fig. 3 shows the percentage of conductor loss, dielectric loss and radiation loss of both GCPW and SICL configurations introduced in Fig. 1. Similar dielectric losses are found for the SICL and GCPW lines. The increase in conductor loss is expected, since the SICL transmission line is encapsulated by additional conducting walls. Most importantly, the radiation losses were eliminated. This is especially critical at higher frequencies, where an increase in radiation loss is observed for the GCPW-line. Moreover, it allows stacking multiple routing layers on top of each other without EMI issues. Simulations with a shared wall of vias between two parallel lines in the

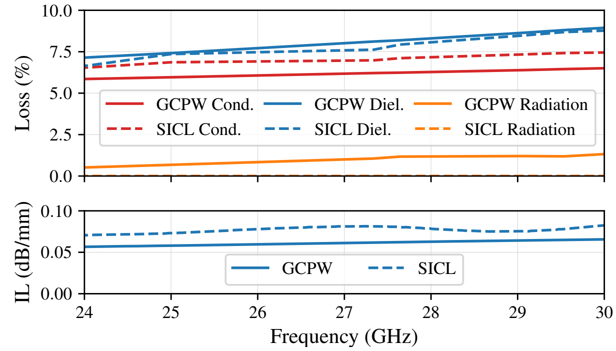

Fig. 3. Comparison of (top) the simulated conductor (Cond.) loss, dielectric (Diel.) loss and the radiation loss for GCPW (solid) and SICL (dashed) lines, and, (bottom) the measured insertion loss (IL) per millimeter.

advocated SICL technology show no degradation in performance, enabling further miniaturizing of the routing networks. The measured average insertion loss of 0.075 dB/mm in case of SICL is only slightly higher than the average 0.065 dB/mm obtained for GCPW.

III. Functional Components

As essential building blocks for beamsteering networks [5], this section investigates two important passive mmWave components, being a multi-layer transition and a hybrid coupler, implemented in SICL technology.

A. Coaxial Via Transition

A 50 Ω coaxial via transition is designed with minimal insertion loss. Fig. 4 shows the layout of this transition with a 1 mm-long SICL line. A photo of the partial PCBs employed to assemble the prototype, is shown on the right of Fig. 4. The corresponding S-parameters are displayed in Fig. 5. A custom TRL calibration kit is fabricated to de-embed the prototype as close as 1 mm to the actual coaxial via transition, such that it matches the simulated layout accurately.

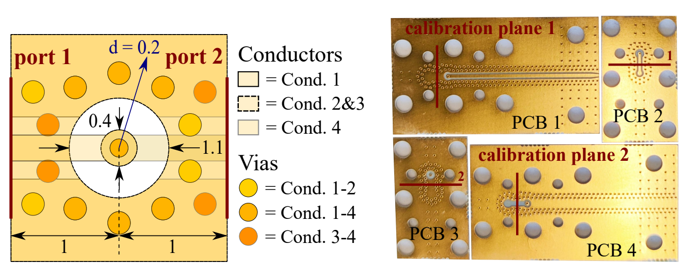

Fig. 4. Coaxial via transition from SICL to SICL with annotated dimensions in millimeter (left) and the corresponding fabrication parts (right).

The measured insertion loss remains within the range 0.55±0.15 dB from 24 GHz to 30 GHz, while the reflection coefficient stays below −13 dB. This is a slight increase compared to the simulated 0.3±0.1 dB insertion loss, caused by the surface finish and surface roughness, which are absent in the simulation model. A major advantage to realize compact routing networks is that the signal conductors on different layers may be rotated in any direction, without performance loss.

To this end, the ground plane between the signal conductors on both layers and the $50\,\Omega$-match of the coaxial via transition are crucial.

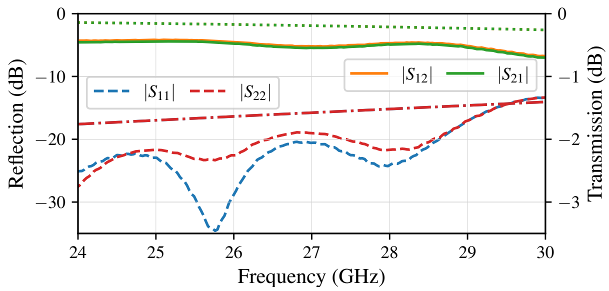

Fig. 5. SICL-to-SICL coaxial via transition: simulated (dashed-dotted) and measured (dashed) reflection coefficient; simulated (dotted) and measured (solid) transmission coefficient.

B. Hybrid Coupler

We also propose a packaged hybrid coupler based on SICL-technology, including a transition towards GCPW for measurement purposes. The component is fed by a $2.2\,\mathrm{mm}$-long GCPW section, remaining after TRL calibration, which in turn transitions into a $3.5\,\mathrm{mm}$-long SICL line at all four ports, before connecting to the actual hybrid coupler design. This is illustrated by the layout in Fig. 6, where the corresponding unassembled fabricated prototype is displayed as well.

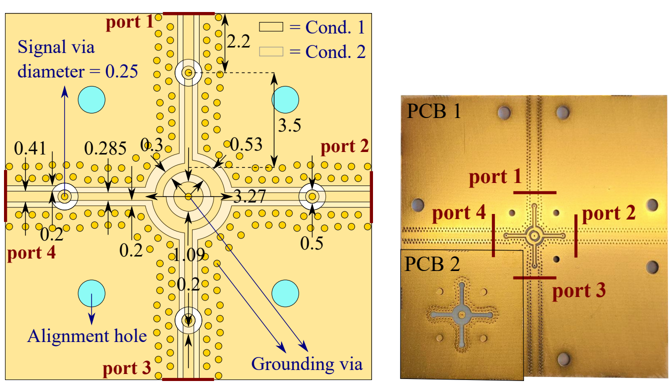

Fig. 6. Proposed SICL-based hybrid coupler with transition to GCPW with annotated dimensions in millimeter (left) and the corresponding fabricated prototype parts before assembly (right).

Its measured S-parameters (top), amplitude imbalance and phase difference (bottom) are presented in Fig. 7. The measurements correspond very well to the simulation, with a measured excess insertion loss of $1.2\pm0.25\,\mathrm{dB}$ from $26.5\,\mathrm{GHz}$ to $29.5\,\mathrm{GHz}$, on top of the $3\,\mathrm{dB}$ power split, which is slightly higher than the simulated value $0.7\pm0.4\,\mathrm{dB}$ due to the employed surface finish and pertinent surface roughness. Simulations show that the influence of an air gap is negligible, since a $5\,\mu\mathrm{m}$-gap between both PCBs amounts to a maximal additional loss of $0.1\,\mathrm{dB}$ over the entire frequency range. The measured amplitude imbalance between both output ports remains smaller than $0.5\,\mathrm{dB}$ from $26.5\,\mathrm{GHz}$ to $29.5\,\mathrm{GHz}$, while the phase imbalance stays below $6°$.

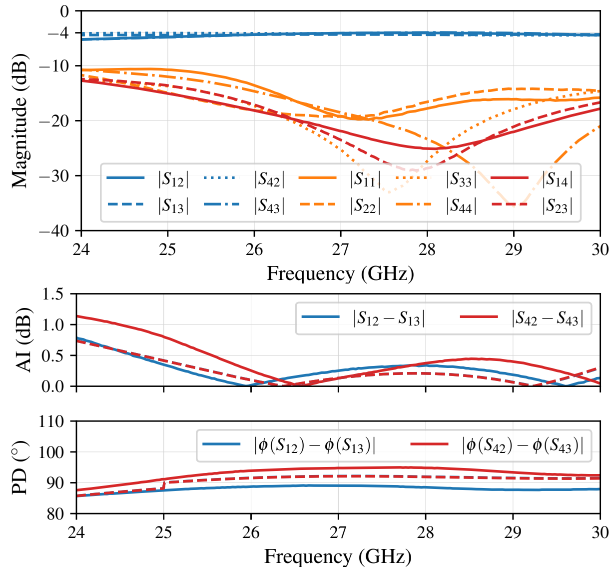

Fig. 7. (top) The measured S-parameters, (bottom) the measured (solid) and simulated (dashed) amplitude imbalance (AI) and phase difference (PD).

IV. Conclusion

This paper presented a cost-effective fabrication process, based on the assembly of single-layer standard printed circuit boards (PCBs), to realize highly shielded substrate integrated coaxial lines (SICLs). The measured average insertion loss of the SICL, over a frequency range from $24\,\mathrm{GHz}$ to $30\,\mathrm{GHz}$, amounts to $0.075\,\mathrm{dB/mm}$, which is approximately the same value for the grounded co-planar waveguide on the same substrate, being $0.065\,\mathrm{dB/mm}$, but without any spuriously radiated fields. The proposed SICL-to-SICL transition has a measured average insertion loss of $0.55\,\mathrm{dB}$. Finally, we have shown a novel SICL-based hybrid coupler with a measured excess insertion loss smaller than $1.45\,\mathrm{dB}$, an amplitude imbalance not exceeding $0.5\,\mathrm{dB}$ and a phase imbalance within $6°$ of its nominal value. During the conference, a completely packaged beamsteering antenna array will be shown.

References

[1] L. Van Messem et al., "Substrate integrated components for passive millimeterwave-frequency beamforming networks," 2021 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications, pp. 272–274, Nov. 2021.

[2] F. Gatti, M. Bozzi, L. Perregrini, K. Wu, and R. G. Bosisio, "A novel substrate integrated coaxial line (SICL) for wide-band applications," 2006 European Microwave Conference, pp. 1614–1617, Sept. 2006.

[3] S. Yang, Z. Yu, and J. Zhou, "A low-loss broadband planar transition from ground coplanar waveguide to substrate-integrated coaxial line," IEEE Microwave and Wireless Components Letters, vol. 31, no. 11, pp. 1191–1194, Nov. 2021.

[4] M. Bozzi, F. Xu, D. Deslandes and K. Wu, "Modeling and design considerations for substrate integrated waveguide circuits and components," 2007 8th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, pp. P-VII–P-XVI, Sept. 2007.

[5] 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.