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RESEARCH ARTICLE

Substrate integrated waveguide E-plane tapering in lowtemperature co-fired ceramic

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Abstract

This letter discusses the design, manufacture, and characterization of a substrate-integrated waveguide E-plane tapering. The tapering facilitates the integration of two waveguides with varying heights for, that is, conductorbacked coplanar waveguide to rectangular waveguide integration. A simultaneous top- and bottom-sided, $\lambda/4$ -based stepped tapering for the 71–86 GHz band is designed using low-temperature co-fired ceramic technology. The fabricated design is measured using two E-plane taperings in back-to-back configuration. The reflection coefficient better than -11.8 dB, and the transmission coefficient larger than -1.4 dB at the full 71–86-GHz range for a single tapering is extracted from the measurement using time-gating.

KEYWORDS

E-band, low-temperature co-fired ceramic (LTCC), substrate-integrated waveguide (SIW)

1 | INTRODUCTION

Increasing demand for higher transmission rates in current and future mobile communications have steered research WILEY

towards millimeter waves (mm waves). The E-band for communication, covering the frequency ranges 71–76 and 81–86 GHz, has been introduced as a good candidate for future backhaul radio links due to the wide band available.¹ The 76-81GHz frequency range is also utilized in automotive radar systems.²

For mm waves, substrate-integrated waveguides (SIW) are used to construct various microwave components, for example, high-Q filters and low-loss transmission lines for signal distribution.3-5 However, the integration of integrated circuits (IC) with SIW is challenging. The integration usually requires a transition from the SIW to a conductor backed coplanar waveguide (CBCPW) of equal height to interface with the ICs. The dimensions of the CBCPW, in particular the height, need to be much smaller than the wavelength. This, however, results in a lossy SIW, as the conductive losses in a SIW increase with decreasing height of the SIW. As an example, Figure 1 shows the simulated insertion loss of a SIW as a function of the height of the SIW. The insertion loss can be up to three times higher in a 92-um thick SIW when compared to a 736-um thick SIW with equal width and length. When the difference in insertion loss between thin and thick SIWs is higher than insertion loss of two E-plane taperings, a thicker SIW with E-plane taperings should be considered.

The SIW E-plane tapering proposed in this letter facilitates the use of higher and, hence, less lossy SIWs together with integrated components. Two-sided tapering allows to locate the IC in a cavity, thus, protecting the IC and bonding wires from physical damage. The proposed E-plane tapering could also be used to create intersections for the full-height SIW in the same substrate. The height of two intersecting SIW could be altered to enable crossing without interference.

Tapered mm-wave waveguide transitions have been proposed previously, but they require precision milling or other fine mechanics.^{6,7} A single-sided SIW tapering has been presented using normal PCBs for lower frequencies.⁸

At mm waves, the small size of the components presents problems for the manufacturing since the manufacturing tolerances are relative to the component size. This also limits the choices for manufacturing technique. The Ferro A6M-Ebased low-temperature co-fired ceramic (LTCC) process at VTT provides high accuracy and repeatability.⁹ LTCC technology allows the use of multiple stacked, equally thin layers.¹⁰

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FIGURE 1 Insertion loss of the SIW as a function of the height at 78.5 GHz. Dimensions are in mm [Color figure can be viewed at wileyonlinelibrary.com]

The height transition inside the LTCC provides advantages compared transitions inside normal dielectric waveguide. Precision milling of tilted surfaces is replaced by the normal LTCC assembly process. This does not require additional milling of waveguide as the transitions are located inside the LTCC.

Our novel implementation in LTCC tapers the SIW in E-band (71–86 GHz). It also employs simultaneous tapering from the top and bottom resulting in shorter transition. The paper is organized as follows: Section 2 presents the proposed design, Section 3 presents the simulation and measurement results, Section 4 examines the results, and Section 5 concludes the paper.

2 | PROPOSED SIW E-PLANE TAPERING DESIGN

Connecting transmission lines with different characteristic impedances together results in discontinuity and reflection. The quarter-wave transformer is the common method to mitigate reflections from multiple discontinuities.¹¹ The reflections from the consecutive changes are summed up in opposite phase and a very low reflection coefficient for the entire transition is achieved. The same approach can be applied to SIWs by using E-plane tapering steps as discontinuities.

In the proposed SIW tapering, the height of the SIW is gradually changed by introducing height steps. The vertical waveguide walls are realized with via fences and horizontal side walls as metal layers. The distance between these steps is approximately λ /4 inside the SIW. Figure 2(A) shows the proposed design and detailed dimensions. Dimensions for the SIW are based on the dielectric waveguides in Reference 12. The width of the SIW is set to 1.48 mm. The height of the SIW is based on the chosen number of layers. One layer in the finished LTCC design is 92 µm thick. Thus, the implemented eight-layer-thick structure yields a SIW height of 0.736 mm. Simulations are performed with LTCC parameters of $\varepsilon_r = 5.7$ and tan $\delta = 0.002$. Gold conductors are used in the simulations ($\sigma = 7*10^6$ S/m). The structure is simulated with CST Microwave Studio.

As the wavelength in the SIW does not vary as a function of height, the length of each step was fine-tuned at 78.5 GHz with the EM-simulator to obtain the optimal length of 395 μ m. Figure 2(B) shows the progressive transition. To minimize the transition length, the two-sided stepping (top and bottom) was chosen for the first two steps. The later transition steps are one-sided in order to determine the single-layer SIW off-center location. In the SIW wall, the via spacing was set to the minimum of 250 μ m (2.5x via diameter) according to the design specification.⁹ All vias are 100 μ m in diameter. The pitch of the via fence used in vertical height step was set to the minimum equal pitch of 263 μ m between SIW walls.

Figure 3(A) shows an additional ground-signalground (GSG)-to-SIW transition, that is designed for the proposed E-plane tapering for measurement purposes. Figure 3(B) illustrates the designed transition structure with the combined CBCPW-GSG transition and E-plane SIW tapering. Figure 3(c) shows the EM-simulation results that indicate a reflection coefficient ($|S_{11}|$) level of -11.5 dB or better for the desired 71-86 GHz frequency band. The transmission coefficient ($|S_{21}|$) for the same band is between -1.0 and -0.7 dB.

The measured response for the single tapering is extracted from the back-to-back measurement of structure IV (shown later) using time gating. This results in |



FIGURE 2 (A) 3-D representation of the proposed structure. (B) The structure from the side. The waveguide ports are shown in blue. Dimensions in µm [Color figure can be viewed at wileyonlinelibrary.com]



FIGURE 3 (A) Structure and dimensions (in μm) of the GSG-to-SIW transition from the top. (B) The combined GSG-to-SIW and SIW E-plane tapering where Port 1 is a 150-μm pitch 50 Ω GSG port and Port 2 is the waveguide port. (C) The simulated S-parameters in dashed line and the time-gated S-parameters from the structure IV measurement in solid line [Color figure can be viewed at wileyonlinelibrary.com]

 $S_{11}| \le -11.8$ dB and $|S_{21}| = -1.4$ to -1.1 dB for the design frequency range. As seen in Figure 3(C), acceptable performance of this structure extends up to 96 GHz.

3 | BACK-TO-BACK SIMULATIONS AND MEASUREMENTS

The measurement of the single E-plane tapering is difficult due to different port-types. Thus, a back-to-back configuration is chosen in order to measure manufactured prototypes in a probe station. The behavior of the single E-plane transition can be extracted using time-gating.

Four different back-to-back GSG-SIW-GSG test structures are simulated, manufactured, and measured. The SIW lengths are adjusted so that test structures with one waveguide of constant height of one SIW layer (92 μ m) and the structures with two E-plane taperings both have the same total length measured from GSG to GSG. In the simulations, all GSG ports are simulated with discrete 50- Ω ports. Prototypes with two different total lengths of 6.47 and 9.72 mm, their structures, and their corresponding measurement results are shown in Figure 4. Short prototypes without and with E-plane transition are named as structure I and II. Long prototypes are named as structure III and IV, respectively.

Based on the simulations, the single layer thick structures I and III have reflection coefficient lower than -10 dBover the whole frequency range and insertion loss of 1.6 and 2.4 dB or less, respectively. For the E-plane structures II and IV, the -10 dB frequency range is slightly narrower in the high frequency end. Insertion loss for these in the full band is 2.2 and 2.7 dB or less, respectively.

The results show that the operation frequency of the simulated structures is higher than that predicted by simulations. The frequency shift is most notable in the structures I and III. The behavior of the reflection coefficient is caused by small reflections in the GSG-SIW transition. Shift in the frequency response indicates a change in electrical length between these reflections. A difference between the design parameters and actual material parameters would explain the shift. This could be the dielectric constant and the effective conductivity and surface roughness of the gold conductor. Prototypes II and IV show similar behavior in the frequency domain.

Therefore, we inspect the results by adjusting the observation band from 72 to 87 GHz. The measured $|S_{11}|$ of the E-plane tapering structure (IV) is less than -7.3 dB and $|S_{11}|$ of the constant height reference structure (III) is less than -10.6 dB. All the results are summarized in Table 1.

The measured reflection coefficients in Figure 4 are higher resulting in stronger variation in the transmission coefficient. We suspect that this is caused by the difference between the GSG-port model used in the simulations and the real GSG-probe. Also the rough surface of the gold conductor might cause contact problems with GSGprobes.



FIGURE 4 (A) Top-view of the manufactured prototype, 3D figure of the simulation model, and simulated (dashed line) and measured (solid line) S-parameters for structure I. (B)-(D) show the same for structures II, III, and IV [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Figure 5 shows the simulated and the measured S_{21} from structures III and IV. For easier comparison, these are presented with time-gating in order to demonstrate the performance of two E-plane transition without the multiple

reflections present in the results shown in Figure 4. Figure 5 (A) demonstrates the simulated insertion loss of equal length lines III and IV. These results support the premise that the thicker SIW can yield lower losses even with the two E-plane taperings than the slim constant height SIW. The structure with E-plane taperings (IV) has smaller insertion

	S ₁₁ max (dB)	S ₂₁ max (dB)	S ₂₁ min (dB)
I sim.	-14.8	-1.5	-1.6
I meas.	-11.8	-1.6	-2.8
II sim.	-7.8	-1.2	-2.2
II meas.	-8.2	-1.7	-3.2
III sim.	-13.6	-2.2	-2.4
III meas.	-10.6	-2.2	-2.7
IV sim.	-7.4	-1.4	-2.7
IV meas.	-7.3	-1.8	-3.7

loss between 67.8 and 92.6 GHz than the single layer thick SIW (III).

The time-gated |S₂₁| measurements in Figure 5(B) show that the operation frequency has shifted higher when compared to the simulations. This shift is in line with other measurements. These results show that the performance between 70 and 95 GHz is similar in the single layer SIW and the Eplane tapered SIW structures. The E-plane tapered SIW has two additional transitions and still achieves approximately the same performance as the single layer SIW. Based on the measurements, the E-plane transition can be used to provide integration to low-loss SIW and also be used to provide SIW E-plane tapering for crossing SIW transmission lines.

Small manufacturing errors were observed in a visual inspection. The deviation between fabricated and designed structures is mostly around few μ m and ranges up to 20 μ m. The manufactured structure IV was converted from the recorded image to the EM-model and re-implemented in the EM-simulation. The modified EM-model shifted the simulated operational frequency slightly towards the measured response over 71–86 GHz frequency band (Figure 6(A)). The modified EM-simulation IV and the measured prototype IV were also compared in time domain. Figure 6(B) shows the propagation time through the structure. The propagation time did not change when the observed deviations in the manufactured structure were implemented to the EM-model. The propagation time is



FIGURE 5 Time-gated |S21| (A) simulations from Structures III and IV and (B) measurements from structure III and IV [Color figure can be viewed at wileyonlinelibrary.com]



FIGURE 6 (A) Time-gated |S11| of the original structure, the modified structure based on the manufactured For Peer Review prototype, the modified structure based on the manufactured prototype with lower dielectric constant, and the measured prototype. (B) Time domain |S21| of the original structure, the modified structure based on the manufactured prototype, the modified structure based on the manufactured prototype with lower dielectric constant, and the measured prototype with lower dielectric constant, and the measured prototype with lower dielectric constant, and the measured prototype [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Comparison of E-plane transition designs; only one transition considered

Design	Туре	Technology	Simulated BW (-10 dB) (GHz)	Measured BW (-10 dB) (GHz)	Simulated IL (dB)	Measured IL (dB)
This work	Stepped	LTCC	68-91	68-96	< 1.4	≈1.4
6	Stepped	Milling	16-20	16-20	N/A	N/A
7	Stepped	Milling	75-110	N/A	<1.0	N/A
8	Stepped	PCB	19-21, 27.8-32.6	19-21, 27.8-30.0	≈1.0	≈2.5

b 12 2 Comparison of E-phate transition designs, only one transition considered

approximately 1 ps lower in the measured prototype which indicates a lower than expected dielectric constant due to higher propagation speed. Based on the EM-simulations, a decrease of 0.2 in the dielectric constant of the LTCC can cause a 1.6-GHz increase in the resonance frequency of the design (IV), see Figure 6. This corresponds to 0.8-ps decrease in the propagation time through the structure. Changes in the loss tangent of the LTCC or conductivity of the gold paste conductors did not yield noticeable change to the resonance frequency of the design.

Thus, we concluded that the differences in the performance of our design are likely due to mismatch in the material parameters. This work provides a manufactured prototype and measurement results for a low loss E-plane SIW transition to cover the E-band utilizing LTCC technology. Similar E-plane transition designs and their main characteristics are listed for comparison in Table 2. Comparison values are for single E-plane transitions only.

For future work, a longer back-to-back configuration design with improved design material parameters could be studied. This could further demonstrate the relationship between length dependent losses in SIW and one time losses in the E-plane tapering.

5 | CONCLUSION

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A novel E-plane tapering based on LTCC structures for E-band is presented. This transition helps with integration of microwave components and helps to minimize conduction losses by enabling the use of SIWs having different heights. The functionality of the prototype was demonstrated with back-to-back measurements, and a single E-plane tapering with $|S_{11}| \le -11.8$ dB and $|S_{21}| \ge -1.4$ dB were measured using time-gating for the 71–86 GHz frequency band.

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