A K/Ka-Band Reconfigurable Substrate Integrated Coaxial Line to Waveguide Transition Technology

YIFANG WEI¹, (Graduate Student Member, IEEE), CHRISTIAN ARNOLD², JIASHENG HONG³, (Fellow, IEEE)

¹School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom (e-mail: y.wei@hw.ac.uk)
²Tesat-Spacecom GmbH & Co. KG Backnang, Germany (e-mail: Christian.Arnold@tesat.de)
³School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom (e-mail: J.Hong@hw.ac.uk)

Corresponding author: Yifang Wei (e-mail: y.wei@hw.ac.uk).

This work was supported by the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 811232.

ABSTRACT In this article, the designs of the K/Ka-Band reconfigurable Substrate Integrated Coaxial Line (SICL)-to-waveguide transitions are presented. Two types of reconfigurable SICL-to-waveguide transitions, with stepped impedance transformers waveguide transitions and ridge waveguide transitions, are designed for two operation frequency modes (K/Ka-band). Both simulated and experimental results are presented for the demonstration. Results indicate that the reconfigurable waveguide structure has the advantages of broad bandwidth and low return loss for both K/Ka-band compared with the conventional dual-band waveguide transitions. The presented waveguide transition designs with high function flexibility will be significant to satellite communication applications and massive MIMO beamforming networks with an active phased antenna array.

INDEX TERMS SICL-to-waveguide transition, dual-band, satellite communication, multilayer MIMO beamforming.

I. INTRODUCTION

In modern satellite communications beamforming technologies, the beamforming system needs dual-band operation frequencies for separate uplink and downlink to reduce the influence and interference [1]. In other words, the transmission (Tx) and reception (Rx) systems are usually frequency separated to achieve a better downlink margin [2].

Due to the wider bandwidth requirement for higher frequency designs, the high-frequency transmission line structures developed rapidly in recent years. The Substrate Integrated Coaxial Line (SICL) structure has the advantages of compact footprint, wide bandwidth, low loss, and interference in high-frequency applications [3]. It is also applicable in a multilayer PCB feeding network, which is promising for reducing the size of the feeding network and increasing the design diversity and flexibility in a MIMO beamforming system. Compared with the coaxial interconnections and transitions to the phased antenna array in a beamforming system, the waveguide transitions have merits in their simple installation and maintenance, which are also popular in RF communication applications for their low loss, wideband performance, and simple structure [4]–[11]. Therefore, SICL-to-waveguide transition designs have great potential for a multilayer MIMO beamforming technology to achieve more flexible functions, especially in satellite communication applications.

Microstrip-to-waveguide transitions were designed with good insertion loss and compact structure [4]–[9]. To be more applicable for a high-frequency multilayer network, SICL-to-waveguide and Substrate Integrated Suspended Line (SISL)-to-waveguide transition designs demonstrated their wideband performance and low loss [10] [11]. However, they are all focused on a single-band operation. Dual-band designs to achieve dual K/Ka-band operation performance in a satellite communication system were presented recently [12]–[14]. They commonly sacrifice bandwidth and performance to achieve dual-band operations. Furthermore, some dual-band waveguide transition designs have operation frequency range limitations [13].

Therefore, the motivation for this work is to develop...
waveguide transitions at K/Ka-band (20 GHz/30 GHz). For this purpose, the two types of reconfigurable SICL-to-waveguide vertical transitions with two operation frequency modes (K/Ka-band) were developed. They provide promising solutions to achieve better wideband performance for the K/Ka-band separated Rx and Tx, which traditionally have two different systems for Rx and Tx with different dimensions. These two types of reconfigurable SICL-to-waveguide transitions have the same waveguide dimension for the same operation mode. Furthermore, the two K/Ka-band mode waveguides share the same SICL PCB feeding network in beamforming applications. Only metallic waveguide parts need to be replaced to achieve K/Ka-band (Tx/Rx) operation modes switching, saving cost, simplifying installation and maintenance, and providing flexible functions.

II. DESIGN OF THE SICL-TO-WAVEGUIDE TRANSITION

In a beamforming system, the SICL-to-waveguide transition connects the feeding network in PCB and the waveguide antenna array. An example of a 2×2 beamforming antenna array is illustrated in Fig. 1 to show the beamforming system network. The phase and gain control section would be installed at the bottom of the multilayer PCB feeding network.

A. RECTANGULAR WAVEGUIDE TRANSITIONS WITH STEPPED TRANSFORMERS

The SICL structure, shown in Fig. 2, provides low loss and wideband performance for a high-frequency multilayer PCB feeding network in a beamforming system. Its two side rows of metallic vias reduce resonance interference in the beamforming feeding network in a compact structure [3].

The adaptable patches on top of the PCB could help match the impedance for the two modes and reduce the interference between them to achieve dual-mode operations at K/Ka-band, shown in Fig. 3 (a) and (b). Contrary to the conventional designs, the two modes for K/Ka-Band share the same PCB feeding network. The waveguide parts with two different dimensions for K/Ka-band connect to the same PCB. They can be installed and replaced easily (screws), as demonstrated in Fig. 1, to achieve different modes of operation at different frequencies.

II. DESIGN OF THE SICL-TO-WAVEGUIDE TRANSITION

In a beamforming system, the SICL-to-waveguide transition connects the feeding network in PCB and the waveguide antenna array. An example of a 2×2 beamforming antenna array is illustrated in Fig. 1 to show the beamforming system network. The phase and gain control section would be installed at the bottom of the multilayer PCB feeding network.

A. RECTANGULAR WAVEGUIDE TRANSITIONS WITH STEPPED TRANSFORMERS

The SICL structure, shown in Fig. 2, provides low loss and wideband performance for a high-frequency multilayer PCB feeding network in a beamforming system. Its two side rows of metallic vias reduce resonance interference in the beamforming feeding network in a compact structure [3].

FIGURE 1: Beamforming system network.

The stepped transformers are adopted in this waveguide transition design to increase the impedance from SICL to the waveguide and convert the propagation mode from quasi-TEM in a SICL to TE10 in a waveguide [15]. The side view and top view of the rectangular SICL-to-waveguide transition with stepped transformers are illustrated in Fig. 4 (a) and (b), and the E-field distributions are shown in Fig. 5 (a) and (b).

FIGURE 2: SICL structure with dimensions.

FIGURE 3: Concept of two modes switched for the SICL-to-waveguide transitions for (a) K-band mode and (b) Ka-band mode. The dimensions are a1 = 9, b1 = 4.5, a2 = 8.5, b2 = 4.25, all in millimeters.

The stepped transformers are adopted in this waveguide transition design to increase the impedance from SICL to the waveguide and convert the propagation mode from quasi-TEM in a SICL to TE10 in a waveguide [15]. The side view and top view of the rectangular SICL-to-waveguide transition with stepped transformers are illustrated in Fig 4 (a) and (b), and the E-field distributions are shown in Fig. 5 (a) and (b).

FIGURE 4: (a) Side view and (b) top view of the rectangular SICL-to-waveguide transition with stepped transformers. The dimensions are L = 11, WK = 28, WKa = 12, d1K = 26.5, d1Ka = 29, LK = 37, LKa = 21, all in millimeters.

To meet the requirements in a beamforming system to provide a better antenna elements distance for better performance at K/Ka-band, there is a dimension limitation of 10 mm for every element. Therefore, the broad wall width of the K-band and Ka-band modes waveguides in this design are 9 mm and 8.5 mm, respectively. When the broad wall is 9 mm,
FIGURE 5: E-field distributions of (a) the waveguide port and (b) the waveguide part in the SICL-to-waveguide transition with stepped transformers.

the cut-off frequency is around 16.7 GHz, and the waveguide still works in the required frequency range for K-band. The narrow wall width is around half of the broad wall width.

The SICL structure and the waveguide are connected by a via, whose equivalent circuit model is shown in Fig. 6 (a) [16]. The stepped transformers from via (Zvia) to waveguide (Zws) could be represented by the equivalent circuit model shown in Fig. 6 (b) [17]. The reactive energy of the fringing fields at each waveguide step is represented by susceptances B1, B2, B3 and B4. The Zd1, Zd2 and Zd3 represent the impedances of stepped transformers.

FIGURE 6: Equivalent circuit models of (a) Via and (b) stepped transformers.

The simulation results in Fig. 7 (a) and (b) show the wideband performance for K/Ka-band operation modes with the bandwidth of 36.6% (18.1 GHz - 26.2 GHz) and 38.1% (21.7 GHz - 31.9 GHz) for return loss better than 10 dB, respectively.

FIGURE 7: Simulated results of waveguide transitions with stepped transformers for (a) K-band mode and (b) Ka-band mode.

B. RIDGE WAVEGUIDE TRANSITIONS

The reconfigurable ridge waveguide transitions have a similar design to the waveguide transitions with stepped transformers to achieve K/Ka-band dual-mode operation by using the adaptable patches on top of the PCB. The identical waveguide dimensions and adaptable patches make these two types of SICL-to-waveguide transitions match the same PCB feeding network in a beamforming system for the same operation mode.

The ridge waveguide structure is adopted in this design to get a broader bandwidth performance [18] [19]. The loss of waveguide transitions with stepped transformers for K-band mode below 18 GHz increases due to its cut-off frequency being around 16.7 GHz. The ridge waveguide structure provides a lower TE10 cut-off frequency for better bandwidth performance for the same broad wall width to meet the requirements for a beamforming system.

The side view and top view of the ridge structure SICL-to-waveguide transition are illustrated in Fig. 8 (a) and (b), and the E-field distributions are shown in Fig. 9 (a) and (b).

The ridge SICL-to-waveguide transitions simulation results are shown in Figs. 10 (a) and (b). They demonstrate wider bandwidth performance for both K/Ka-band operation modes with a bandwidth of 50.5% (16.3 GHz - 27.3 GHz).
and 43.7% (20.4 GHz - 31.8 GHz) for return loss better than 10 dB, respectively, compared with the SICL-to-waveguide transition with stepped transformers.

FIGURE 8: (a) Side view and (b) top view of the ridge SICL-to-waveguide transition. The dimensions are \( L = 11, \ WK = 28, \ WKa = 12, \ d1K = 26.5, \ d1Ka = 29 \), all in millimeters.

FIGURE 9: E-field distributions of (a) the waveguide port and (b) the waveguide part in the ridge SICL-to-waveguide transition.

In a beamforming application, adding an 8.5 mm \( \times \) 4.25 mm to 9 mm \( \times \) 4.5 mm waveguide transition to the K-band mode waveguide port does not significantly influence the performance and helps the two modes designs have the same waveguide dimension on both K/Ka-band. Therefore, the two K/Ka-band waveguides could connect and feed the same wideband waveguide antenna array in a beamforming system with separated Rx and Tx, improving flexibility and cost-efficiency and simplifying installation.

The cavity height \( L \), via diameter \( Dv \), ridge depth \( d1 \) and stepped transformer width \( W \) are critical to these two SICL-to-waveguide transition designs. The analysis in Figs. 11 (a), (b), (c), and (d) demonstrates the effects of these transition parameters on the K-band mode ridge SICL-to-waveguide transition. The cavity height \( L \) is critical for the propagation mode transformation from a SICL to a waveguide. The via diameter \( Dv \) and width \( W \) of the ridge (or the stepped transformers) significantly influence the operation frequency range. The operation range moves to a higher frequency when the via diameter \( Dv \) increases or the ridge width \( W \) decreases. The ridge depth \( d1 \) helps the impedance matching to get better performance.

III. EXPERIMENT RESULTS

A grounded coplanar waveguide (GCPW) structure was deployed and extended from the SICL to the edge of the test ports on a K-connector to facilitate experimental testing of the two kinds of designed SICL-to-waveguide vertical transitions. The fabricated SICL-to-waveguide transition is shown in Fig. 12 (a). The back-to-back structure was used in the measurement, shown in Fig. 12 (b). The measured and simulated results of the SICL-to-waveguide transition with stepped transformers and the ridge SICL-to-waveguide transition are shown in Figs. 13 (a) and (b) and Figs. 13 (c) and (d), respectively. The measured insertion loss and
return loss results agree relatively well with the simulations (including the connectors and the GCPW structures). The higher insertion loss and the small difference are due to the fabrication tolerance.

**FIGURE 11:** Simulated reflection coefficients for different parameters. (a) Various values of cavity height $L$, (b) various values of via diameter $D_v$, (c) various values of stepped transformer width $W$ and (d) various values of ridge depth $d_1$.

The SICL-to-waveguide transition with stepped transformers measured minimum insertion loss (per transition) is 1.2 dB for K/Ka-band. The measured back-to-back structure bandwidths (return loss below 10 dB) are around 35.8% (17.4 GHz-25.0 GHz) and 25.0% (24.5 GHz-31.5 GHz) for K/Ka-band, respectively.

The ridge SICL-to-waveguide transition measured minimum insertion loss (per transition) is 1.0 dB and 1.1 dB for K/Ka-band, respectively. The measured back-to-back structure bandwidths (return loss below 10 dB) are around 41.2% (16.2 GHz-24.6 GHz) and 45.2% (20.2 GHz-32.0 GHz) for K/Ka-band, respectively.

Both reconfigurable SICL-to-waveguide vertical transitions with stepped transformers and ridge SICL-to-waveguide vertical transitions provided wideband performance at K/Ka-band. Table 1 summarised and demonstrated the performance of recently published waveguide transition designs. Compared with the recent dual-band waveguide transition designs (with around 3% to 16% bandwidth), most waveguide transition designs with a single operational frequency band mode have better wideband performance and insertion loss. The comparison shows that the two presented designs have considerably better wideband performance than the recent dual-band waveguide transitions with around 25% to 45% measured bandwidth and could achieve the dual-band operation at K/Ka-band simultaneously by using the reconfigurable structure. Furthermore, the sizes (estimated dimensions of the transition designs which exclude the 50-ohm input and waveguide output) of all cited designs and these two proposed designs are listed in the table. The proposed designs have a compact footprint with 0.7λ and 0.9λ dimensions for K/Ka-band, respectively, applicable for an antenna array in MIMO beamforming applications at K/Ka-band.

**FIGURE 12:** (a) Fabricated SICL-to-waveguide transitions and (b) the back-to-back structure in the measurement.

**IV. CONCLUSION**

A K/Ka-band reconfigurable SICL-to-waveguide transition technology has been presented in this article. Two SICL-to-
waveguide vertical transition designs with stepped transformers and ridge structures were designed and tested to demonstrate the design concept. Simulated and measured results had a good agreement and showed wideband performance in K/Ka-band. Furthermore, the developed SICL-to-waveguide transitions exhibit properties of reconfigurable structures and flexible functions. The presented transition technology is promising for future use in a multilayer MIMO beamforming system in satellite communication applications with all these distinctive characteristics.

ACKNOWLEDGMENT
Yifang Wei is a research fellow of TESLA (Advanced Technologies for future European Satellite Applications) project which has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 811232.

Meanwhile, Yifang Wei would like to acknowledge the collaboration and technical support from Tesat-Spacecom GmbH & Co. KG.

REFERENCES
[1] P. B. Saha, R. Kumar Dash and D. Ghoshal, "A Compact Uplink-Downlink Band Switchable Wideband Antenna for C-band Satellite Applications," 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN), 2020, pp. 262-266, doi: 10.1109/SPIN48934.2020.9071293.

[2] S. Cakaj and K. Malaric, "Isolation measurement between uplink and downlink antennas at low earth orbiting satellite ground station," 2007 19th International Conference on Applied Electromagnetics and Communications, 2007, pp. 1-4, doi: 10.1109/ICECEM.2007.4544490.

[3] Y. Wei, C. Arnold and J. Hong, "A K/Ka-Band Substrate Integrated Coaxial Line Power Divider for 4-input and 16-output Beamforming Multi-Layer Feeding Network." 2020 IEEE Asia-Pacific Microwave Conference (APMC), 2020, pp. 929-931, doi: 10.1109/APMC47863.2020.9331438.

[4] M. Sarkar and A. Majumder, "A Novel Broadband Microstrip to Waveguide Transition at W band with High Manufacturing Tolerance Suitable for MMIC Packaging." 2018 IEEE MTT-S International Microwave and RF Conference (IMaRC), 2018, pp. 1-4, doi: 10.1109/IMaRC.2018.877214.

[5] X. Dai, "An Integrated Millimeter-Wave Broadband Microstrip-to-Waveguide Vertical Transition Suitable for Multilayer Planar Circuits," in IEEE Microwave and Wireless Components Letters, vol. 26, no. 11, pp. 897-899, Nov. 2016, doi: 10.1109/LMWC.2016.2614973.

[6] E. Topak, J. Hasch and T. Zwick, "Compact Topside Millimeter-Wave Waveguide-to-Microstrip Transitions," in IEEE Microwave and Wireless Components Letters, vol. 23, no. 12, pp. 641-643, Dec. 2013, doi: 10.1109/LMWC.2013.2284824.

[7] A. Artemenko, A. Maltsve, R. Maslenkov, A. Sevastyanov and V. Sosin, "Design of wideband waveguide to microstrip transition for 60 GHz frequency band," 2011 41st European Microwave Conference, 2011, pp. 838-841, doi: 10.23919/EuMC.2011.6101966.

[8] C. Wu, Y. Zhang, Y. Xu, B. Yan and R. Xu, "Millimeter-Wave Waveguide-to-Microstrip Transition With a Built-In DC/IF Return Path," in IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 2, pp. 1295-1304, Feb. 2021, doi: 10.1109/TMTT.2020.3041257.

[9] Z. Xu, J. Xu and C. Qian, "Novel In-Line Microstrip-to-Waveguide Transition Based on E-Plane Probe T-Junction Structure," in IEEE Microwave and Wireless Components Letters, vol. 26, no. 1, pp. 52-54, Feb. 2016, doi: 10.1109/LMWC.2015.2482523.

[10] M. Jiang, W. Hong, Y. Zhang and H. Zhou, "A broadband waveguide to substrate integrated coaxial line (SICL) transition for w-band applications," 2014 Asia-Pacific Microwave Conference, 2014, pp. 70-72.

[11] Y. Chen, K. Ma and Y. Wang, "A Ka-Band Substrate Integrated Suspended Line to Rectangular Waveguide Transition," in IEEE Microwave and Wireless Components Letters, vol. 28, no. 9, pp. 744-746, Sept. 2018, doi: 10.1109/LMWC.2018.2849203.

[12] K. Erkelzen, L. P. B. Bohl, A. Sieganschin and A. F. Jacob, "A Compact K-/Ka-Band Rectangular-to-Coaxial Waveguide Transition With Integrated Diplexer," in IEEE Microwave and Wireless Components Letters, vol. 31, no. 6, pp. 642-645, June 2021, doi: 10.1109/LMWC.2021.3064673.

[13] H. A. Diawuo and Y. -B. Jung, "A Novel K/Ka-Band Rectangular-to-Coplanar Waveguide Transition." 2020 IEEE Asia-Pacific Microwave Conference (APMC), 2020, pp. 929-931, doi: 10.1109/APMC47863.2020.9331438.
FIGURE 13: Measured results of the back-to-back waveguide transitions with stepped transformers for (a) K-band mode and (b) Ka-band mode; Measured results of the back-to-back ridge waveguide transitions for (c) K-band mode and (d) Ka-band mode.
CHRISTIAN ARNOLD was born in Heilbronn, Germany, on June 26th 1980. He received the Dipl.-Ing. (BA) (B.A.) from the Berufskademie Mosbach, Germany in 2003 and the Dipl.Ing. (M.S.) from the Universität Stuttgart in 2007. From August 2005 to May 2006 he studied at the University of Arizona in Tucson, Arizona. In March 2007 he joined Tesat Spacecom GmbH in Backnang, Germany, as RF design engineer in the passive microwave products development group. His areas of focus are reconfigurable and temperature compensated filters and multiplexers for space applications. He holds several patents in these areas. In 2017, he received his Ph.D. degree at Universität Karlsruhe (TH), Germany. Today, he is working at Tesat spacecom with a focus on active antennas and digital modulator products.

JIASHENG HONG (Fellow, IEEE) received the D.Phil. degree in engineering science from the University of Oxford, Oxford, U.K., in 1994.

He then joined the University of Birmingham, Birmingham, U.K., until 2001, when he moved up to Edinburgh, U.K., to join Heriot-Watt University, Edinburgh, where he is currently a Professor leading a team for research into advanced radio frequency (RF)/microwave device technologies. He has authored or coauthored over 200 journal articles and conference papers in this field and has published four relevant books: Microstrip Filters for RF/Microwave Applications (Wiley, first edition, 2001, and second edition, 2011), RF and Microwave Coupled-Line Circuits (Artech House, second edition, 2007), Balanced Microwave Filters (Wiley, 2018), and Advances in Planar Filters Design (IET, 2019).

Dr. Hong is also a member of the IEEE MTT Technical Committees, the Subject Editor (Microwave) of Electronics Letters, and an Associate Editor of IET Microwaves, Antennas & Propagation and International Journal of RF and Microwave Computer-Aided Engineering.

***