International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Compact low-cost substrate integrated waveguide fed antenna for 122 GHz radar applications

Martin Frank[1], Fabian Lurz[1], Robert Weigel[1] and Alexander Koelpin[2]

[1]Institute for Electronics Engineering, Friedrich-Alexander University Erlangen-Nuremberg (FAU), 91058 Erlangen, Germany and [2]Chair for Electronics and Sensor Systems, Brandenburg University of Technology, 03046 Cottbus, Germany

Research Paper

Cite this article: Frank M, Lurz F, Weigel R, Koelpin A (2019). Compact low-cost substrate integrated waveguide fed antenna for 122 GHz radar applications. *International Journal of Microwave and Wireless Technologies* **11**, 408–412. https://doi.org/10.1017/S1759078719000072

Received: 9 October 2018
Revised: 9 January 2019
Accepted: 10 January 2019
First published online: 20 February 2019

Keywords:
Antenna design; substrate integrated waveguide; antenna measurements

Author for correspondence:
Martin Frank, E-mail: martin.frank@fau.de

Abstract

This paper describes the design and characterization of a compact substrate integrated waveguide (SIW) fed antenna for the 122 GHz industrial, scientific, and medical band. The use of a single RO4350B substrate layer and the SIW feeding ensure a low-cost fabrication. Two versions of the antenna are presented differing in antenna gain and size. For measurement purpose, a transition from rectangular waveguide to SIW is introduced. Measurements of the radiation pattern have been performed and show good agreement with the numerical results for both antennas and an antenna gain up to 7.14 dBi.

Introduction

The 122 GHz industrial, scientific, and medical (ISM) frequency band is very attractive for radar and wireless communication applications because of the license-free access and the high frequency and bandwidth allowing high-resolution measurements or high data rates. Antennas are a key element in every radar system. They are responsible for the spatial radiation and influence the available range and the bandwidth of the system. At frequencies above 60 GHz, the antennas are often placed on chip [1,2] or integrated in different package technologies [3,4]. Nevertheless, there have been approaches to design antennas on printed circuit boards (PCB) above 100 GHz using patch antennas [5,6] with expensive high-frequency laminates. When usingsubstrate integrated waveguide (SIW) structures as feed leaky wave antennas [7–9] are a common choice. Typically leaky wave antennas only focus the radiating fields in one plane unless using an array approach with several parallel SIW lines. Both, patch antennas and leaky wave antennas, radiate with the Poynting vector approximately perpendicular to the PCB plane.

The aim of this work is to develop a suitable antenna for a discrete SIW six-port radar system on low-cost PCB technology operating at 122 GHz which requires lateral radiation of the antennas similar as presented in [10] for 61 GHz. There has been previous research published on Vivaldi-shaped antennas which are often also using a SIW feeding structure. The main difference to our work is that those antennas are mostly operating at a significant lower frequency band [11–15]. Therefore, the published approaches had less challenging requirements regarding substrate material and fabrication tolerances and process. Designs covering frequencies up to 90 GHz [16] or even 120 GHz [17] demand substrate cutouts or gaps in the substrate metallization below 100 μm leading to increasing manufacturing costs. Additionally, none of those designs feature the cost-efficient Rogers RO4350B substrate. The antenna design presented in the following sections uses a similar SIW fed Vivaldi structure and is supposed to operate in the 122 GHz ISM band. To ensure low manufacturing costs and fast prototyping at those very high frequencies, the antenna is based on a very low-cost Rogers RO4350B substrate and designed as simple as possible to be not relied on substrate cutouts, structures below 100 μm or any other configuration making the manufacturing process more complex.

Antenna design

The SIW technology is very suitable for high-frequency circuit design [18]. The electric characteristics are only dependent on the placement of the vias and the material properties of the substrate. Therefore, no expensive PCB fabrication technology is necessary to achieve very tiny structures as usually needed in high-frequency design.

The whole design is based on a single double-sided metallized RO4350B high-frequency substrate. The height of the substrate is chosen to 0.254 mm. The main advantage of this substrate is the low price compared with other high-frequency substrates. The datasheet [19] provides values for the dielectric constant and dissipation factor only up to 40 GHz respectively 10 GHz. The frequency range of this work clearly exceeds those limits. The losses are expected

© Cambridge University Press and the European Microwave Association 2019. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution, and reproduction in any medium, provided the original work is properly cited.

CAMBRIDGE UNIVERSITY PRESS

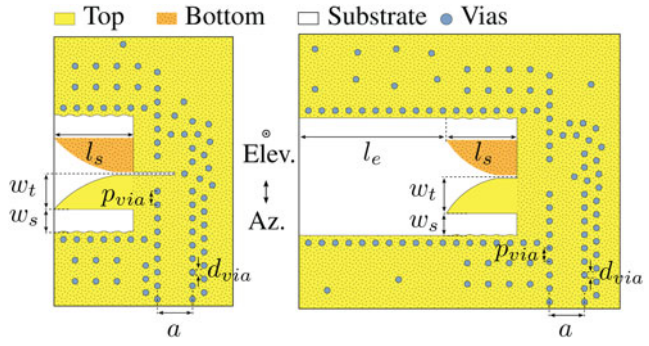


Fig. 1. Layout of the SIW fed vivaldi-shaped antenna 1 (left) and extended substrate antenna 2 (right) with the main design parameters (top view).

to be significantly higher and a design ϵ_r of approximately 3.0 has been derived from previous designs. For the SIW feed line, an insertion loss of approximately 2.4 dB/cm could be discovered.

The actual antenna design is based on a similar approach for the 61 GHz ISM band presented in [20] and modified for operation at 122 GHz without any additional layers or shielding. The structure of the first developed antenna with SIW feed is depicted in Fig. 1 on the left with some of the main design parameters for the antenna structure and the SIW feed. The antenna structure is placed in right angles to the SIW feed line. A Vivaldi-shaped structure and a slot on both metallic layers are used to guide the fields to the edge of the substrate. A via placed in the SIW line directs the fields from the SIW line into the antenna structure. The exact placement of the via can be used for matching purpose.

The transmission characteristics of the SIW line are mainly dependent on its width a which is chosen to 1.17 mm. The diameter of the vias $d_{via} = 0.2$ mm and the via spacing $p_{via} = 0.45$ mm are a compromise between transmission behavior and PCB manufacturing technology. The dimensions of the antenna structures $l_s = 2.65$ mm, $w_t = 1.19$ mm, and $w_s = 0.775$ mm are optimized regarding the radiation pattern and the input matching. The total width (3.93 mm) and length (3.45 mm) of the antenna are both below $2\lambda_0$. Therefore, the directivity of the element might be limited. Fig. 2(a) shows the simulated electric field distribution in cross-section for the designed antenna with SIW feed radiating into free-space at 122.5 GHz. The simulated radiation pattern for this antenna is shown in Fig. 3(a) at 122.5 GHz. The design results in high directivity in the azimuth plane and a gain of 5.54 dBi.

In order to increase the antenna gain, a second version of the antenna has been developed. The modified antenna structure is presented in Fig. 1 on the right. Compared with the previous version, the substrate behind the Vivaldi structure is extended by the length l_e. Instead of radiating direct into free-space, the wave is guided inside the substrate by a via fence to the edge of the PCB. Additionally, the feeding of the Vivaldi structure is simplified by the removal of the slot. Therefore, the new design is making less demands to the PCB manufacturing process.

Simulations resulted in the length $l_e = 4.935$ mm to maximize the antenna gain. The other dimensions were slightly adjusted to match the antenna structure to the SIW feed resulting in $l_s = 2.36$ mm, $w_t = 1.23$ mm, and $w_s = 0.738$ mm. The parameters of the SIW feed p_{via}, d_{via}, and a are identical for both antenna designs. The simulated electric field distribution for the second antenna is depicted in Fig. 2(b). It can be observed that the small tilt of the main beam direction in the azimuth plane for antenna 1 is corrected by the second design.

The directivity pattern of the second antenna structure is also presented in Fig. 3(b). The design shows an improved gain of 7.87 dBi at 122.5 GHz. Additionally, the directivity in the elevation plane is increased. The simulated free-space reflection coefficient is presented in Fig. 4(a) for both antenna designs with and without the transition. The pure antennas show good matching over a wide frequency range. The transition slightly limits the bandwidth and decreases the matching. Fig. 4(b) shows the simulated *S*-parameters of the proposed transition in back-to-back-configuration. The 122 GHz ISM band is well covered.

Measurement results

The characterization of the antenna is performed with a vector network analyzer (VNA) and a rotation stage. In order to connect the antenna with the VNA, a transition from rectangular waveguide (WR-06) to SIW is needed. Due to the high frequency, and therefore very small structures, a single slot is placed in the copper of the SIW line to allow coupling from a rectangular waveguide into the substrate. Appropriate drills are provided to attach the flange of the rectangular waveguide (UG-387/U-M) on the SIW line. Fig. 5 shows a photograph of the fabricated antennas with the transition to rectangular waveguide together with a reference for the size of the structures. Additionally, a 24 dBi horn antenna is placed next to the designed and fabricated antennas. It can be clearly seen that the antenna structures itself are very compact. The transition to rectangular waveguide and both antenna structures are highlighted in an enlarged view.

The measured $|S_{11}|$ of both antennas is presented in Fig. 4(a). The measured reflection coefficients clearly differ from the simulated results without transition but match the simulations performed with the transition. The frequency behavior of this transition is strongly dependent on the dimensions of the slot which are subjected to production tolerances, and therefore cause deviations in the measured reflection coefficient of the antenna. Nevertheless, both antennas show acceptable matching during the measurements in the frequency range from 120 to 125 GHz. In Fig. 4(b), the measured *S*-parameters for the transition in back-to-back configuration are compared with simulated results. The main difference can be observed in a considerably higher insertion loss for the measurement. This can be explained with the actual losses in the RO4350B substrate which are higher than the data sheet value, specified at only 10 GHz, used for the simulations. Additionally, it turned out that the size of the fabricated slots for transitions got larger than desired. According to simulations with CST Microwave Studio, this shifts the transmission band of the rectangular waveguide to SIW transition to higher frequencies. This can also be recognized in Fig. 4(b) and has an effect on the measured reflection coefficients in Fig. 4(a). It is important to emphasize that the transition from rectangular waveguide to SIW is only utilized for the characterization of the single components and not required in the final system.

The measurement setup to characterize the antenna radiation pattern is presented in Fig. 6. A horn antenna with a gain of 24 dBi is used as reference antenna. Previous measurements have been performed to determine the insertion loss due to the rectangular waveguide sections and the transition from rectangular waveguide to SIW as presented in Fig. 4(b). The measured gain is corrected with these results. The measured gain and radiation pattern are in good agreement with the numerical results. The

https://doi.org/10.1017/S1759078719000072 Published online by Cambridge University Press

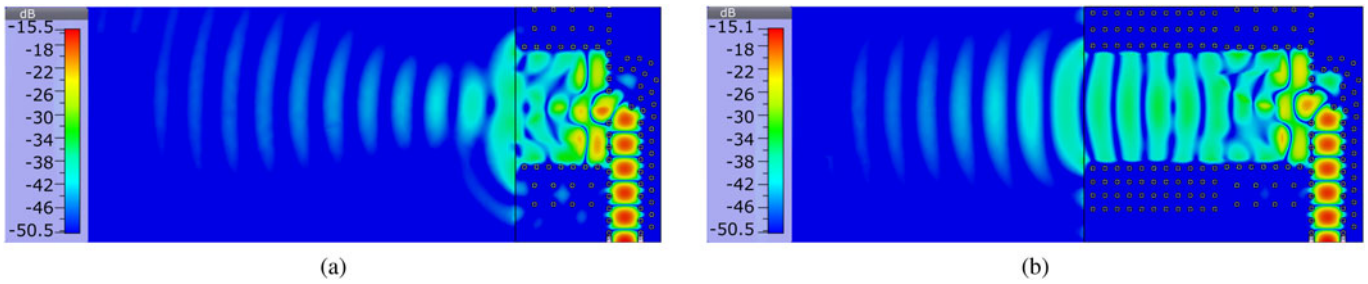


Fig. 2. Simulated electric field distribution of the designed antenna structures with SIW feed and radiation into free-space for (a) antenna 1 and (b) antenna 2.

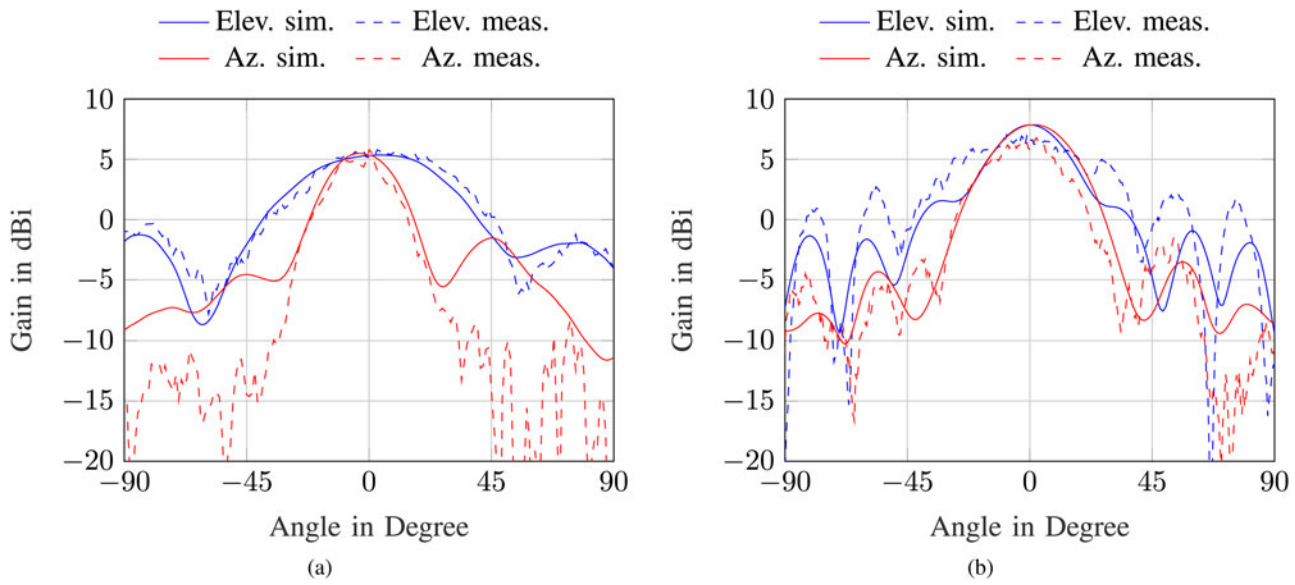


Fig. 3. Simulated and measured radiation patterns in azimuth and elevation for (a) antenna 1 and (b) antenna 2 at 122.5 GHz.

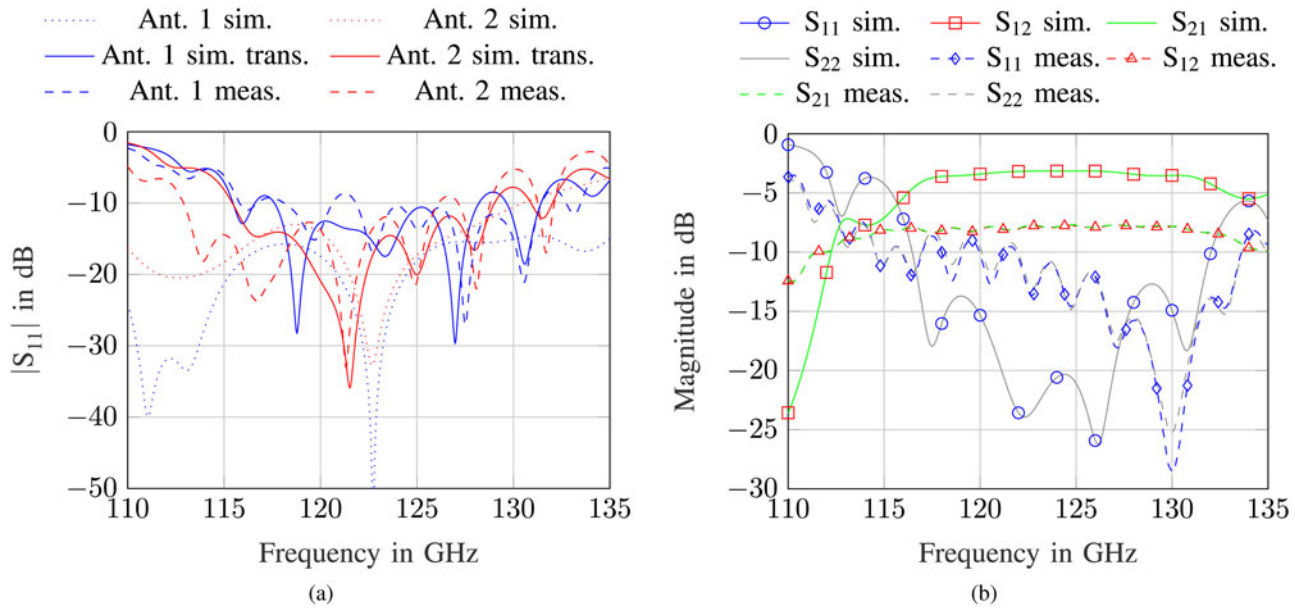


Fig. 4. (a) Simulated and measured free-space reflection coefficient for both antenna designs and (b) simulated and measured *S*-parameters for the transition in back-to-back configuration.

https://doi.org/10.1017/S1759078719000072 Published online by Cambridge University Press

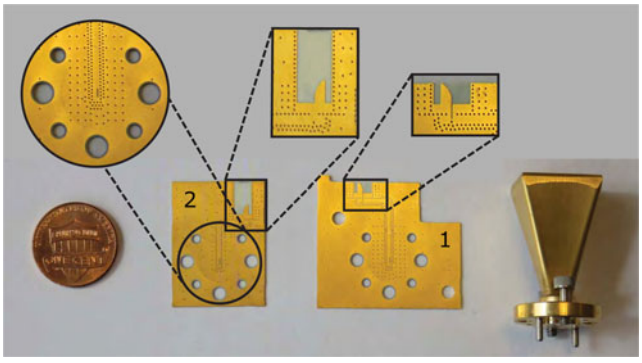


Fig. 5. Photograph of the fabricated antennas 1 and 2 with highlighted transition from SIW to rectangular waveguide and the antenna structures together with a 24 dBi horn antenna in D band.

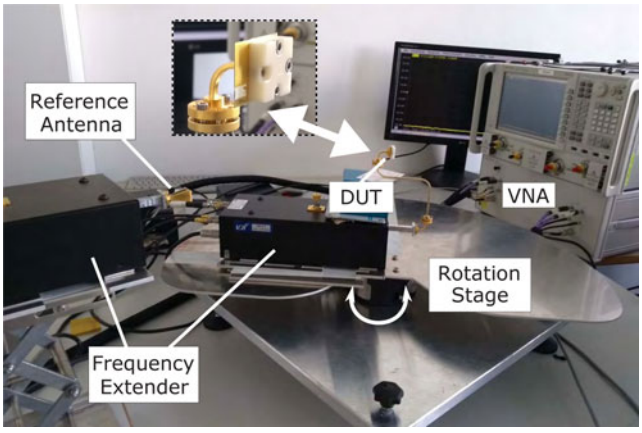


Fig. 6. Measurement setup for the characterization of the radiation pattern and antenna gain.

measured and corrected gain for antenna 1 in Fig. 3(a) is close to the simulated value of 5.54 dBi at 122.5 GHz. The measured gain in Fig. 3(b) for antenna 2 of 7.14 dBi is larger than the gain of antenna 1 but not as high as expected from the simulations. Additional losses in the section of the extended substrate are assumed to cause this deviation. The measured results of the radiation pattern are consistent with the simulations and show the desired radiation behavior over the whole frequency range from 120 to 125 GHz. Both antennas provide low side lobe levels in the azimuth plane. The extended substrate of antenna 2 results in a smaller beamwidth in the elevation plane.

Conclusion

In this work, two different designs of a compact low-cost SIW fed antenna for the 122 GHz ISM band have been presented. The antennas are formed in a single RO4350B laminate. A gain of around 5.4 dBi was measured for the first antenna and could be optimized to 7.14 dBi for the second version by extending the substrate in front of the Vivaldi structure. The measured radiation pattern are in good agreement with the numerical results and show good focusing for a single element antenna. It could be successfully demonstrated that the RO4350B substrate can reasonably be used above 120 GHz for low-cost designs.

Author ORCIDs. Martin Frank, 0000-0001-9640-4277

Acknowledgments. This work has been developed in the project NetGuard6P. NetGuard6P (reference number: 16ES0183) is funded by the German ministry of education and research (BMBF) within the research program InPro3D.

References

1. **Ng HJ and Kissinger D** (2018) Highly miniaturized 120-GHz SIMO and MIMO Radar sensor with on-chip folded dipole antennas for range and angular measurements. *IEEE Transactions on Microwave Theory and Techniques* **66**, 2592–2603.
2. **Goettel B, Pahl P, Kutschker C, Malz S, Pfeiffer UR and Zwick T** (2017) Active multiple feed on-chip antennas with efficient in-antenna power combining operating at 200–320 GHz. *IEEE Transactions on Antennas Propagation* **65**, 416–423.
3. **Beer S, Gulan H, Rusch C and Zwick T** (2012) Coplanar 122-GHz antenna array with air cavity reflector for integration in plastic packages. *IEEE Antennas and Wireless Propagation Letters* **11**, 160–163.
4. **Fischer A, Tong Z, Hamidipour A, Maurer L and Stelzer A** (2014) 77-GHz multi-channel radar transceiver with antenna in package. *IEEE Transactions on Antennas Propagation* **62**, 1386–1394.
5. **Hasan R, Ahmad WA, Lu JH, Kissinger D and Ng HJ** (2018) Design and characterization of a differential microstrip patch antenna array at 122 GHz. *Proceedings of the 2018 IEEE Radio and Wireless Symposium (RWS)*,pp. 28–30.
6. **Herrero P and Schoebel J** (2009) Microstrip patch array antenna technology for 122 GHz ISM sensing applications, *Proceedings of the 2009 German Microwave Conference*,pp. 1–4.
7. **Lyu YL, Meng FY, Yang GH, Erni D, Wu Q and Wu K** (2017) Periodic SIW Leaky-wave antenna with large circularly polarized beam scanning range. *IEEE Antennas Wireless Propagation Letter* **16**, 2493–2496.
8. **Liu j, Jackson DR and Long Y** (2012) Substrate integrated waveguide (SIW) Leaky-wave antenna with transverse slots. *IEEE Transactions on Antennas Propagation* **60**, 20–29.
9. **Sharma A, Sarkar A, Biswas A and Akhtar M** (2018) Substrate integrated waveguide fed dual-frequency dual-linearly-polarized dielectric resonator antenna. *International Journal of Microwave and Wireless Technologies* **10**, 505–511.
10. **Mann S, Will C, Reissland T, Lurz F, Lindner S, Linz S, Weigel R and Koelpin A** (2018) High-precision interferometric radar for sheet thickness monitoring. *IEEE Transactions on Microwave Theory and Techniques* **66**, 3153–3166.
11. **Kazemi R, Fathy E and Sadeghzadeh RA** (2012) Dielectric rod antenna array with substrate integrated waveguide planar feed network for wideband applications. *IEEE Transactions on Antennas and Propagation* **60**, 1312–1319.
12. **Puskely J, Lacik J, Raida Z and Arthaber H** (2016) High-gain dielectric-loaded vivaldi antenna for Ka-band applications. *IEEE Antennas and Wireless Propagation Letters* **15**, 2004–2007.
13. **Hesari SS and Bornemann J** (2017) Wideband circularly polarized substrate integrated waveguide endfire antenna system with high gain. *IEEE Antennas and Wireless Propagation Letters* **16**, 2262–2265.
14. **He SH, Shan W, Fan C, Mo ZC, Yang FH and Chen JH** (2014) An improved vivaldi antenna for vehicular wireless communication systems. *IEEE Antennas and Wireless Propagation Letters* **13**, 1505–1508.
15. **Suo Y, Li W and Chen J** (2016) A SIW antipodal vivaldi array antenna design. *International Journal of Antennas and Propagation* **2016**, 1–10.
16. **Mirbeik-Sabzevari A, Li S, Garay E, Nguyen H, Wang H and Tavassolian N** (2018) W-band micromachined antipodal vivaldi antenna using SIW and CPW structures. *IEEE Transactions on Antennas and Propagation* **66**, 6352–6357.
17. **Taringou F, Dousset D, Bornemann J and Wu K** (2013) Broadband CPW feed for millimeter-wave SIW-based antipodal linearly tapered slot antennas. *IEEE Transactions on Antennas and Propagation* **61**, 1756–1762.
18. **Bozzi M, Georgiadis A and Wu K** (2011) Review of substrate-integrated waveguide circuits and antennas. *IET Microwaves Antennas and Propagation* **5**, 909–920.
19. Rogers Corporation: RO4000 Series High Frequency Circuit Materials, http://www.rogerscorp.com.

https://doi.org/10.1017/S1759078719000072 Published online by Cambridge University Press

20. **Mann S, Lurz F, Linz S, Lindner S, Will C, Wibbing S, Weigel R and Koelpin A** (2016) Substrate integrated waveguide fed antenna for 61 GHz ultra-short-range interferometric radar systems. *Proceedings of the 2016 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*,pp. 64–66.



Martin Frank received the B.Sc. and M.Sc. degrees in electrical, electronics, and communication engineering from the Friedrich-Alexander University Erlangen-Nuremberg (FAU), Erlangen, Germany, in 2012 and 2015, respectively. In 2015, he joined the Institute for Electronics Engineering, FAU, as a Research Assistant. His current research interests include the areas of microwave circuits and antenna design for radar applications.



Fabian Lurz received the B.Sc. and M.Sc. degrees in information and communication technology from the Friedrich-Alexander University Erlangen-Nuremberg (FAU), Erlangen, Germany, in 2010 and 2013, respectively. In 2013, he joined the Institute for Electronics Engineering, FAU, as a Research Assistant. He became the Group Leader of the Electronic Systems Group in 2017. His current research interests include microwave circuits and system, especially for low-cost and low-power metrology applications.



Robert Weigel received the Dr.-Ing. and the Dr.-Ing. habil. degrees, both in electrical engineering and computer science, from the Munich University of Technology in Germany where he respectively was a Research Engineer, a Senior Research Engineer, and a Professor for RF Circuits and Systems until 1996. From 1996 to 2002, he has been Director of the Institute for Communications and Information Engineering at the University of Linz, Austria where, in August 1999, he cofounded the company DICE, devoted to the design of RFICs for mobile radio and MMICs for vehicular radar applications. Since 2002, he is Head of the Institute for Electronics Engineering at the University of ErlangenNuremberg, Germany. Prof. Weigel has been engaged in research and development of microwave theory and techniques, electronic circuits and systems, and communication and sensing systems. In these fields, he has published more than 900 papers.



Alexander Koelpin received his diploma in electrical engineering in 2005, his doctoral degree in 2010, and his "venia legendi" in 2014 all with the University of Erlangen-Nuremberg (FAU), Germany. From 2005 to 05/2017, he was with the Institute for Electronics Engineering, FAU, Germany. From 2007 to 2010, he has been team leader; from 2010 to 2015, group leader Circuits, Systems and Hardware Test; and since 2015, leader of the group Electronic Systems. Since 06/2017, he isa Professor and Head of the Chair for Electronics and Sensor Systems with the Brandenburg University of Technology Cottbus-Senftenberg, Germany. His research interests are in the areas of microwave circuits and systems, wireless communication systems, local positioning, and six-port technology. He has authored or co-authored more than 200 publications in his areas of interest.

https://doi.org/10.1017/S1759078719000072 Published online by Cambridge University Press