Forward

Public Report

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Projekt inom *Trafiksäkerhet och automatiserade fordon*

FFI Fordonsstrategisk Forskning och Innovation

Table of Contents

1 Summary

The global automotive industry is rapidly adapting millimeter wave radar sensor as a key technology within several application areas, where active safety and autonomous driving are in the forefront. High performance automotive radar sensors will have to be developed to cope with the challenges of future active safety aspects and autonomous driving. It is therefore of critical importance that the Swedish automotive industry builds millimeter wave radar sensor competence immediately and starts adapting the technology to become a world leader in this field.

Today's existing automotive radar sensors depend only on the PCB based antenna technology such as microstrip patches. But this PCB based antenna technology cannot be used to improve the performance of the automotive radars due to serious limitation on dielectric losses, isolation problem, routing losses etc. Also, the cost of the PCB based antennas become quite prohibitive if complex antenna design needs to be implemented.

The FORWARD project addressed this need by developing novel integrated antenna and passive sensor concept for future automotive applications. A Swedish invention known as gap waveguide technology has been used to develop several integrated antennas at 77GHz as well as 140GHz frequency range. These antennas have been used to demonstrate new polarimetric of automotive sensors and will be considered as the groundwork for next generation automotive radar solutions with better interference suppression, target detection capabilities. The project also demonstrated sensors for detecting the ice or slippery road in front of the vehicle to assist the driver a priory. All these results of the newly developed technology can be reused by the Swedish automotive industry and will be utilized also in future projects within the field of active safety and autonomous driving. The knowledge and sensor deployment guidelines generated within this project can have a significant impact on future product decisions and are intended for OEMs as well as suppliers.

The project resulted into three PhD dissertations (one PhD defence held in June 2023, one planned in November 2023 and one planned in February 2024), three technical licentiate reports (Licentiate seminars held during 2021-2022 study period), one MSc. Thesis report (held during 2021 study period) and several peer reviewed journal papers and conference papers.

2 Executive summary in Swedish

Den globala fordonsindustrin anpassar snabbt millimetervågsradarsensorn som en nyckelteknik inom flera applikationsområden, där aktiv säkerhet och autonom körning är i framkanten. Högpresterande bilradarsensorer måste utvecklas för att klara utmaningarna med framtida aktiva säkerhetsaspekter och autonom körning. Det är därför av avgörande vikt att svensk fordonsindustri bygger kompetens inom millimetervågsradarsensor omedelbart och börjar anpassa tekniken för att bli världsledande inom detta fält.

Dagens befintliga bilradarsensorer är till stor del beroende av PCB-baserade antennteknik som mikrostrip patch-antenn. Men denna PCB-baserade antennteknik kan inte användas att förbättra prestandan hos bilradarerna på grund av begränsningar pga dielektriska förluster, kopplingseffekter, ledarförluster etc. Kostnaden för de PCB-baserade antennerna blir också hög om en komplex antenndesign behöver implementeras.

FORWARD-projektet åtgärdade detta behov genom att utveckla nya integrerade antenner och passiva sensorkoncept för framtida fordonstillämpningar. En svensk uppfinning som kallas gapvågledarteknik har även använts för att utveckla flera integrerade antenner på 77GHz såväl som 140GHz frekvensområde. Dessa antenner har använts för att demonstrera ny polarimetri av fordonssensorer och kommer att betraktas som grunden för nästa generations bilindustri nämligen radarlösningar med bättre störningsskydd och måldetekteringsmöjligheter.

Projektet undersökte även sensorer för att upptäcka is eller halt väglag framför fordonet. Alla dessa resultat av den nyutvecklade tekniken kan återanvändas av Svensk fordonsindustri och kommer att användas även i framtida projekt inom området aktiv säkerhet och autonom körning. Riktlinjerna för kunskap och sensordistribution som skapats inom detta projekt kan ha en betydande inverkan på framtida produktbeslut och är avsedda för OEM såväl som leverantörer. Projektet resulterade i tre doktorsavhandlingar (en disputation hölls i juni 2023, en planerad i november 2023 och en planerad i februari 2024), tre tekniska licentiatrapporter (Licentiatseminarier hålls under studieperioden 2021-2022), en MSc. Examensrapport (hålls under 2021 studieperiod) och flera referentgranskade tidskrifter och konferensartiklar

3 Background

In the upcoming years, numerous sensors will be developed and installed in a car to serve as a car's "eyes", and support full autonomous driving. These sensors should ensure safety-critical functionality, and this means very tight specifications for object detection and classification. Also, the sensors must be ultra-reliable, and this means the sensors will be performing in every weather condition, in poor lighting, near or far, and with a wide field of view. Automotive radar technology is well-suited to fulfil most of these requirements. Also, automotive radars have always benefited significantly from technological advances, especially in semiconductor technology and packaging, allowing a better performance and much more functionality in the radar frontend. This is evident already with the significant growth of 77GHz radar sales and aggregated number of installed 77 GHz radar sensors in today's cars. However, todays off the shelf 77GHz radar sensors fall short of performance in terms of detailed information of the detected object, reliably to detect vulnerable road users like pedestrians or cyclists, detection of road surface conditions etc.

4 Purpose, research topic and methods

In this proposal '*FORWARD*',

- We aimed to develop antenna solutions to expand and improve the performance of the existing sensors at 77GHz and also we look into antenna solutions for futuristic radar sensors which will be operating around 140GHz. The 77GHz slot array solution will include different circular polarized (CP) antenna design which could be easily placed in an automotive environment. This antenna will be able to generate wider beam and extended FoV without complex beam forming algorithms, compared to the standard solutions available today.
- One 77GHz system has been planned for a passive radiometer sensor working to detect the road condition and the low friction spot in front of the vehicle.
- Moving up in frequency will unquestionably improve the angular resolution and angular accuracy of the automotive sensors. Thus, low cost micromachined 140GHz antennas will be designed and fabricated for the future automotive sensors with better angular resolution for the future automotive vehicles.
- Also a low-loss packaging concept to integrate the RF chip with the metal based waveguide slot array will be investigated within the frequency range of 77-140GHz band.
- Finally, newly developed radar sensors will be demonstrated and tested within the real automotive environment.

Research Topics:

- **Dealing the interference signal and improving the detection probability by using circular polarized (CP) antenna: (WP2)**

As mentioned earlier, interference mitigation is a new challenging topic which has to be addressed with the increasing number of radar sensors installed in future cars. Most radar system uses linear polarization because the radar system can be designed easily. Problem of linear polarization is when two radar systems are confronted each other, the radiated signals from both radars act as an interference signal for each other. Because the interference signal is even larger than the reflected signal from the target, it can desensitize the receiver of the radar. In this project, we propose to unitize the right hand circular polarized (RHCP) antenna and left hand circular polarized (LHCP) antenna for the TX and RX port of the automotive radar to overcome this problem. Also, the CP antennas are able to collect more data from the objects having low RCS value and in this way can improve the detection probability of such objects.

- **Doubling of the angular and range resolution by moving up in frequency (WP3)**

Increasing the operation frequency means operating at shorter wavelengths, allowing either smaller antenna dimensions or a larger electrical aperture at the same mechanical dimensions. A key performance parameter that benefits from a larger antenna aperture is the angular resolution and the associated angular accuracy. Considering the increase of the operational frequency of an established radar system (from 77GHz towards 140GHz) calls for investigating important aspects like the availability of low-cost high performance antenna technology and active circuit technology. However, low cost PCB based antenna technologies face major challenges above 100GHz due to the need of very thin substrate layer (which is not mechanically rigid), achieved tolerance of the PCB and the losses in the dielectric substrates. These challenges could be easily overcome by the proposed low cost polymer micromachined slot array antenna based on gap waveguide technology.

- **Innovative packaging solution for integrating RF chip and the gap waveguide slot array (WP4)**

However, there are plenty of technological factors and mechanical challenges in designing high frequency RF front-ends and the development is greatly hindered due to the lack of robust RF packaging and integration techniques at higher millimeter-wave frequency. These are factors such as cavity modes, radiation from minor bends or discontinuities and coupling and feedback due to surface waves, lossy interconnects etc. In this proposal, we will exploit the newly invented Gap waveguide technology and Gap packaging in such a way that the low loss transitions and interconnects can be realized for chip-to-waveguide integrations.

- **Polarization based sensing for road surface characterization (WP5)**

Polarization based passive sensing will be introduced for detecting the road condition in an automotive environment for all weather condition. The suggested detection method takes advantage of the frontal "natural" illumination of the road surface provided by the cold sky. The sensor will be constructed so that it can discriminate between dry, wet, ice-covered, or other depositions on the surface of the road. This is possible since different materials have substantially different dielectric constants, as for example water and ice. In this project, the frequency will be centered around 85 – 100 GHz for two reasons, first because sky is cold and relatively independent of the weather and second because high-gain and compact antennas can be made at this frequency facilitating the integration of the sensor onto the vehicle.

5 Goals

The most important goals of *FORWARD* were as follows:

- Design, fabrication and characterization for low-cost CP polarized antenna array based on gap waveguide technology.
- Realization of a low cost 140 GHz antenna array with polymer-based fabrication process.
- A radar sensor demonstrator system based on the designed dual CP polarization passive radiometer for road surface detection.
- A sensor demonstrator system based on the dual polarization passive radiometer for road surface detection and characterization.
- Measurement data for validating the theoretical studies with respect to antenna design quality, RF polarization and background radiation detection.
- 3PhD thesis and 3 licentiate theses from Chalmers.

6 Result and goal fullfilment

WP-1: Automotive System level requirement analysis:

In the near future not only upper-class cars will be equipped with various radar applications like collision-warning, surface detection etc to increase traffic safety. Therefore, many high performance radar sensors have to be developed and integrated in the car. This work package investigated the different needs and criteria for future possible radar sensors to be deployed in an automotive environment. Particularly, system level analysis was performed to understand the requirements on angular resolution, range resolution and sensitivity of the sensors. The WP was lead by CEVT.

WP-2: Low cost 77 GHz Slot Array Design with Circular Polarization and design of Conformal array at 77GHz.

In this work package, our primary objective is to develop and characterize a dual circularly polarized (CP) slot array antenna using gap waveguide technology. This innovation aims to minimize mutual interference among multiple sensors. Specifically, we target achieving optimal relative impedance and axial ratio bandwidths within the 76-81 GHz frequency band. Additionally, the package will explore the design of a single-layer geometry to lower the antenna's profile. Both simulated and experimental measurement results for the designed antennas are included in this section to showcase novel design approaches.

Antenna models and results: Related to Deliverable 2.1, 2.2 and 2.3

The two prototypes of single-layer dual-circularly polarized antenna has been developed and are shown in the figures below. They are built with ridge gap waveguide technology and fed by WR12 ports.

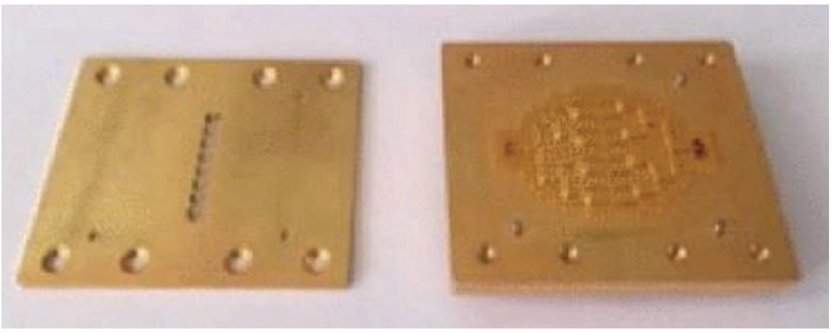

Figure 1 prototype of the dual circular polarized antenna 1. [1]

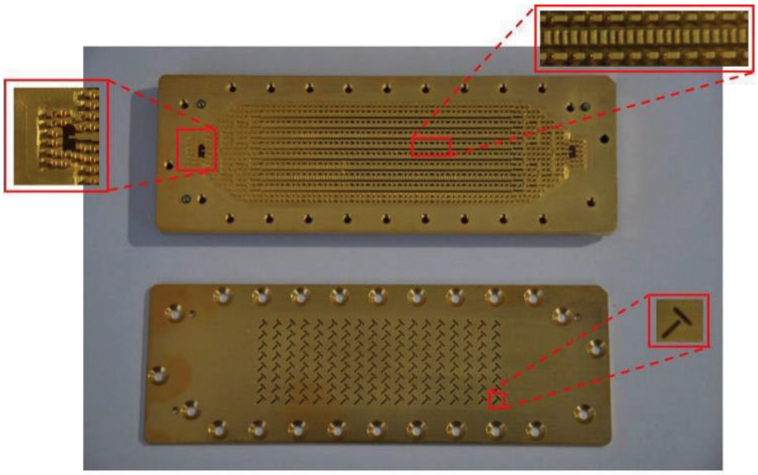

Figure 2 prototype of the dual circular polarized antenna 2. [2]

Measurements results

Lab testing involved using Anechoic chamber at Chalmers and Gapwaves AB. The test setups are shown in the figures below..

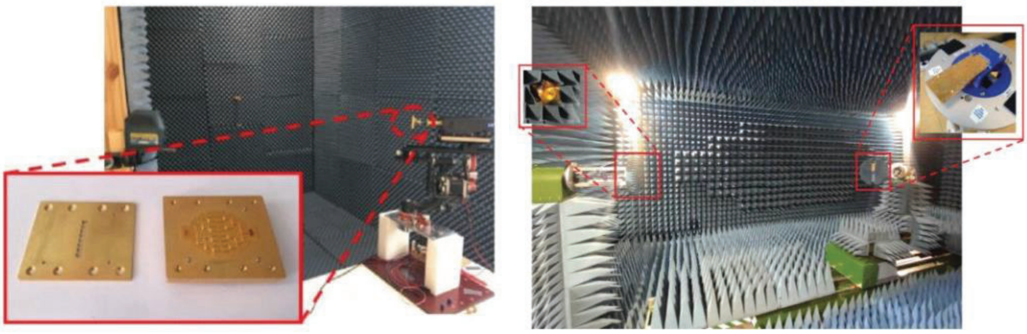

Figure 3 far-field measurement setup at Chalmers and Gapwaves .

The measured results of the two prototypes are shown in figure 4 and figure 5. Both of these two antenna are working at 76-81 GHz with impedance matching lower than -10 dB and axial ratio smaller than 3 dB. More details can be found in the paper by [1,2]

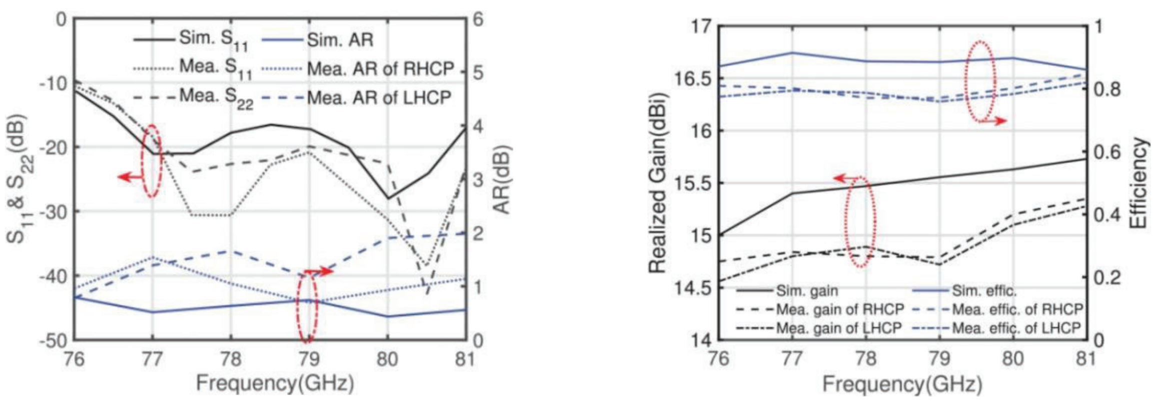

Figure 4 Measurements results of the dual circular polarized antenna 1.

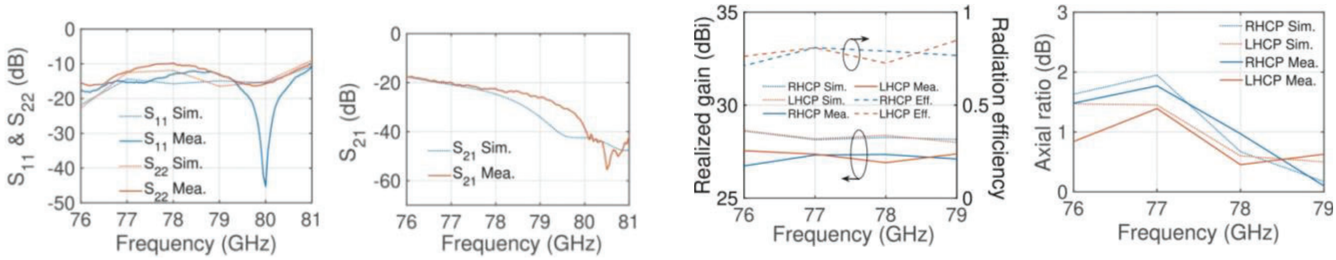

Figure 5 Measurements results of the dual circular polarized antenna 2.

<u>Demonstrator of the full polarimetric radar:</u>

Based on these above two designs, we also built a a comprehensive automotive radar demonstrator which is showcased in fig.6. This demonstrator features a robust antenna system that includes dual-polarization capabilities. Specifically, the receiving unit (RX) is equipped with two Right-Hand Circularly Polarized (RHCP) antennas alongside two Left-Hand Circularly Polarized (LHCP) antennas. On the transmitting end (TX), the system incorporates two RHCP antennas and one LHCP antenna. The entire antenna array is seamlessly integrated into a Texas Instruments AWR2243 radar board. Details pertaining to further measured results will be elaborated upon in subsequent publications.

Figure 6 Demonstrator of proposed radar board.

<u>Conclusion and future work</u>

In summary, two distinct yet complementary studies on dual circularly polarized (CP) antenna arrays have been conducted, each offering valuable insights into their respective applications. Antenna 1 presented a single-layer dual CP antenna array leveraging Gap Waveguide (GW) technology, effectively minimizing electrical loss and enhancing design flexibility. The antenna array exhibited excellent dual CP performance across the targeted frequency range, making it a viable option for automotive radar applications for short to mid-range radar sensors.

Antenna 2 introduced a dual-CP waveguide slot array antenna built on stepped Ridge Gap Waveguide (RGW) technology. The design not only achieved solid CP performance but also delivered impressive far-field results. Its measured port isolation and polarization purity indicate strong potential for use in polarimetric radar applications.

Both studies suggest that dual-CP antenna arrays, whether based on GW or stepped RGW technology, can be seamlessly integrated with commercial radar boards using existing integration concepts. This opens the door for the development of comprehensive radar front-end systems in the future.

WP3 - Low cost Micromachined 140 GHz Slot Array Design

Achieving competitive performance for a low-cost fabrication technologies developed in the project was a target met. The results reached beyond the target of 140 GHz to demonstrate fabrication viability for devices also at >200 GHz frequencies. At the same time the project contribution has resulted in the academic degree of Ph D for the main student involved in the project, Sadia Farjana, [3]. The work has furthermore been published in the following reference scientific papers [4-8]

The work has also been presented at international conferences and workshops with the contributions as follows [9-12]

Summary of key results related to Deliverable 3.1, 3.2 and 3.3

A template-based injection molding process has been designed to realize a high gain antenna operating at D band (110 - 170 GHz). The injection molding of OSTEMER is an uncomplicated and fast device fabrication method. In the proposed method, the time-consuming and complicated parts need to be fabricated only once and can later be reused. The three main parts made of gold plated polymers are dislpayd in figure 7 while the critical stages of the fabrication for the molding of OSTEMER is shown in figure 8. Results of electrical characterization compared to simulations are given in figure 9.

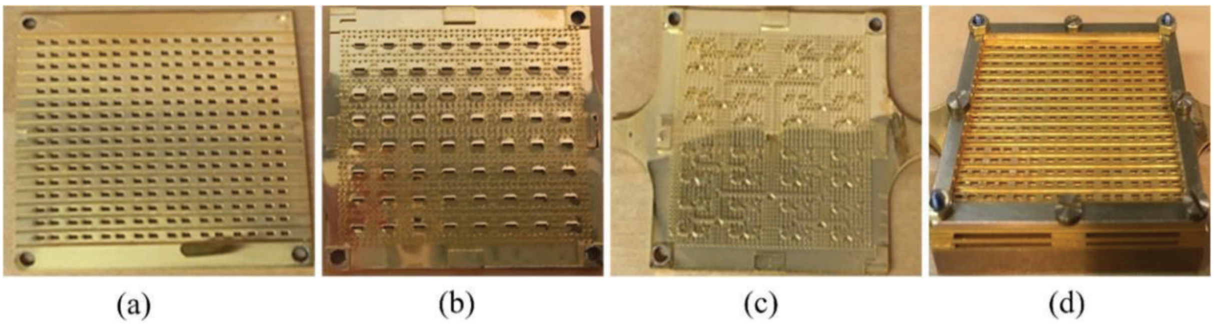

Figure 7: Fabricated antenna, (a) slot layer, (b) feed layer, (c) cavity layer, (d) complete antenna mounted on the milled base plate.

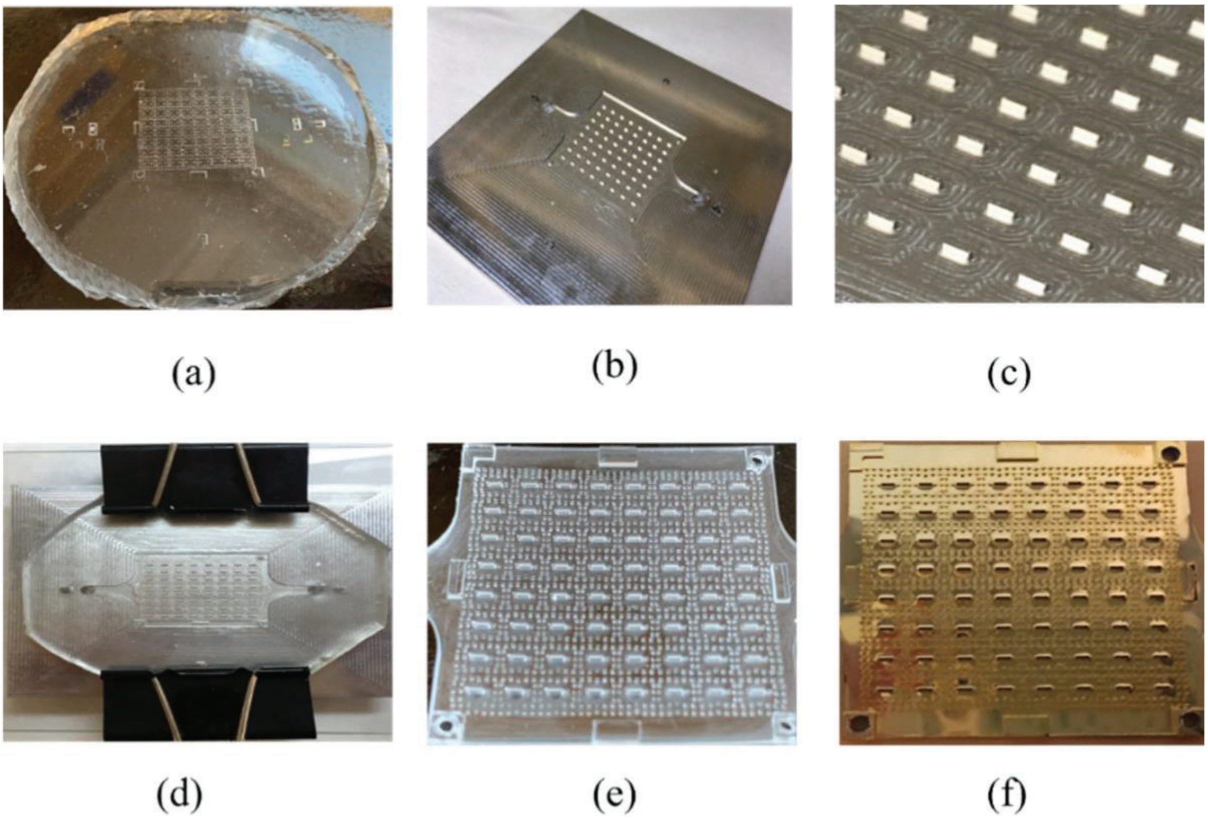

Figure 8: Injection molding steps for the cavity layer. (a) PDMS mold for the cavity layer,(b) aluminum (Al) mold, (c) closed image of the milled Al piece showing the pins to create the cavity opening after injection molding, (d) PDMS mold on top of the aluminum mold, ready for injection molding, (e) cavity layer made of OSTEMER after UV exposure and heat cure, (d) cavity layer after conductive layer deposition.

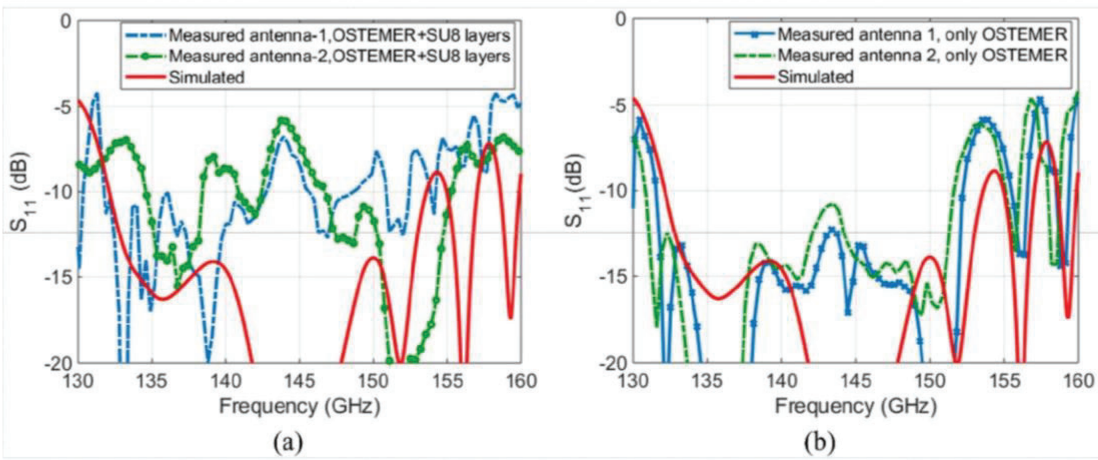

Figure 9: Simulated and measured S11 for the 16×16 element antenna array. (a) The slot layer was made of SU8, the cavity layer, and the feed layer was made of OSTEMER, (b) all layers were made of OSTEMER.

A slot array antenna, shown in figure 10, operating in the D band (140GHz), has been designed based on gap waveguide technology, fabricated by SUEX dry film photoresist. The designed antenna consists of two layers: a slot layer and a feed layer with a transition to measuring waveguide. The antenna contains structures that require a multiple-level dry film fabrication process with thicknesses ranging from 80 µm to 400 µm with ± 10 µm tolerance. The input reflection coefficient was measured to be below – 11 dB over a 10% bandwidth from 136-148 GHz, and the antenna gain was measured to be 11.4 dBi at 142 GHz, both of which are in fair agreement with simulations.

Among the different challenges, one is thermal effects, and these are aggravated when using a polymer as a device material. It is expected that a system will be exposed to a wide range of temperatures during operation. A thermal cycling test in the temperature range −50 to 135 °C with a ramp-up time of 10 min and 30 min dwell time was conducted for 300 thermal cycles. Figure 11 shows the S11 measurement results after 75, 150, and 300 thermal cycles. No clear detrimental effects can be seen on the performance.

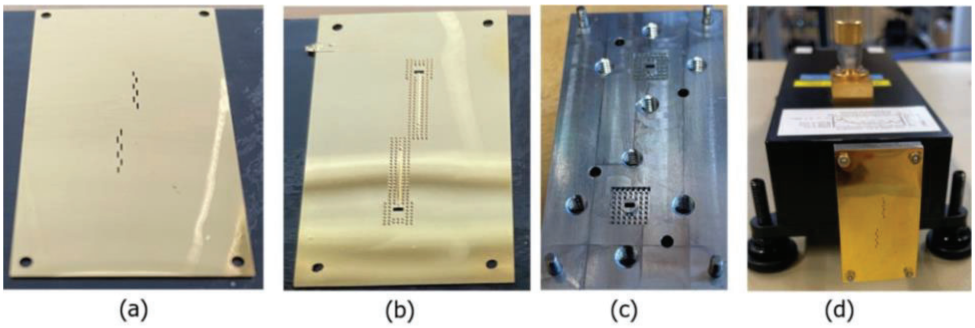

Figure 10: The fabricated antenna, (a) slot layer, (b) feed layer, (c) supporting bottom plate with WR-6.5 opening and gap waveguide pin flange structure, (d) fabricated antenna mounted in the machined supporting plate and connected to the VDI D-band extender.

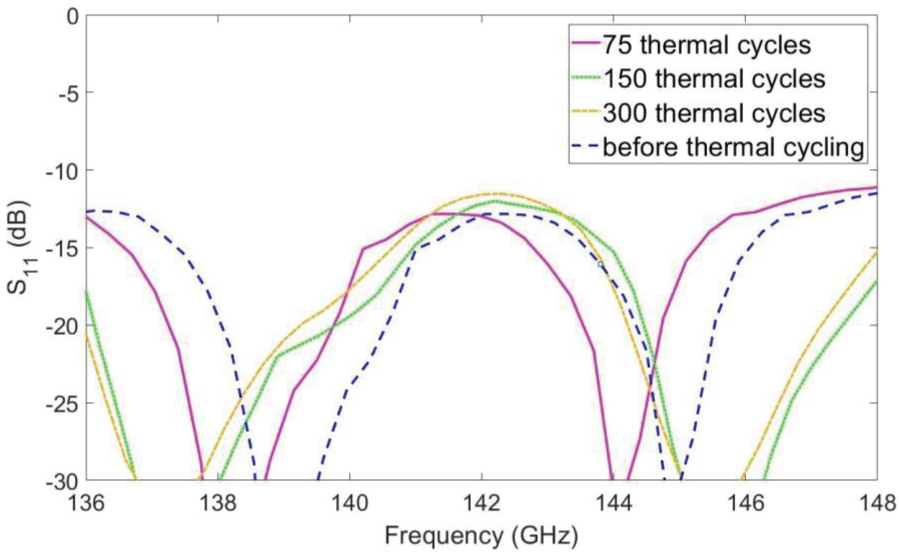

Figure 11: Simulated and measured S_{11} of the fabricated antenna before and after thermal cycling test.

The above-mentioned dry film technology based micromachining has been demonstrated also around 300GHz. Three transmission lines have been designed, fabricated, and demonstrated:

a straight ridge line, a bent ridge line with two 90-degree bends, and a groove gap line. For all these transitions, the waveguide port was located on top of the metal plate of the waveguide. SUEX dry film photoresist has been used for the fabrication of the transitions. The height of the structures is 270 µm, and a 40 µm thick base layer was used to construct the ridge and the pins. The thickness of the base layer is independent of transition performance. Three SUEX dry film sheets of thickness 200 µm, 50 µm, and 20 µm have been used to achieve 270 µm thick structures. Figure 12 shows images of fabricated ridge gap waveguide (RGW) and groove gap waveguide (GGW) chips.

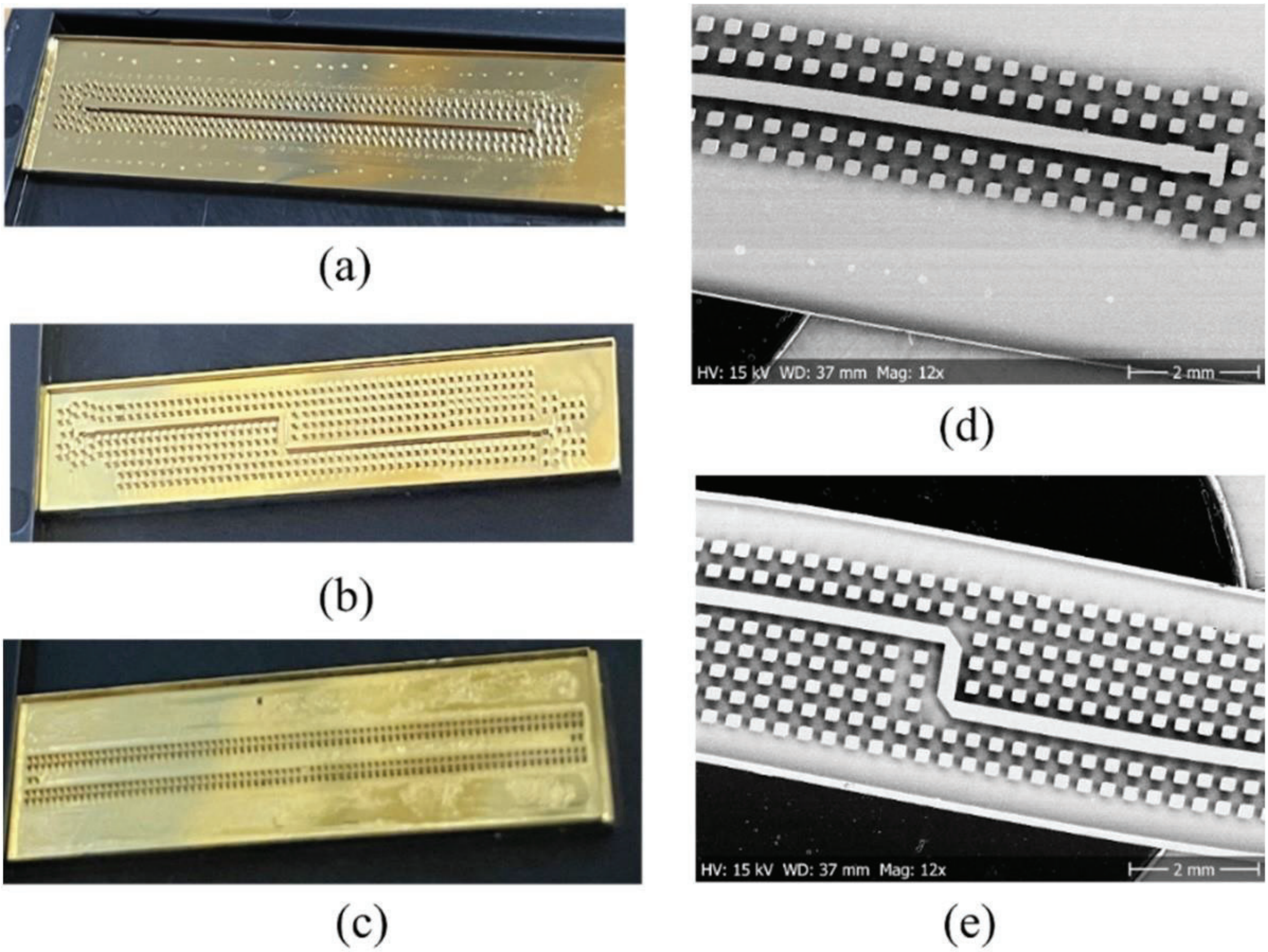

Figure 12: Fabricated chips: (a) straight RGW on chip (b) bent RGW chip, (C) groove GW chip. SEM images of the fabricated chips: (d) straight RGW, (e) bent RGW

Figure 13 shows the simulation and measured S-parameters of back-to-back transmission lines.

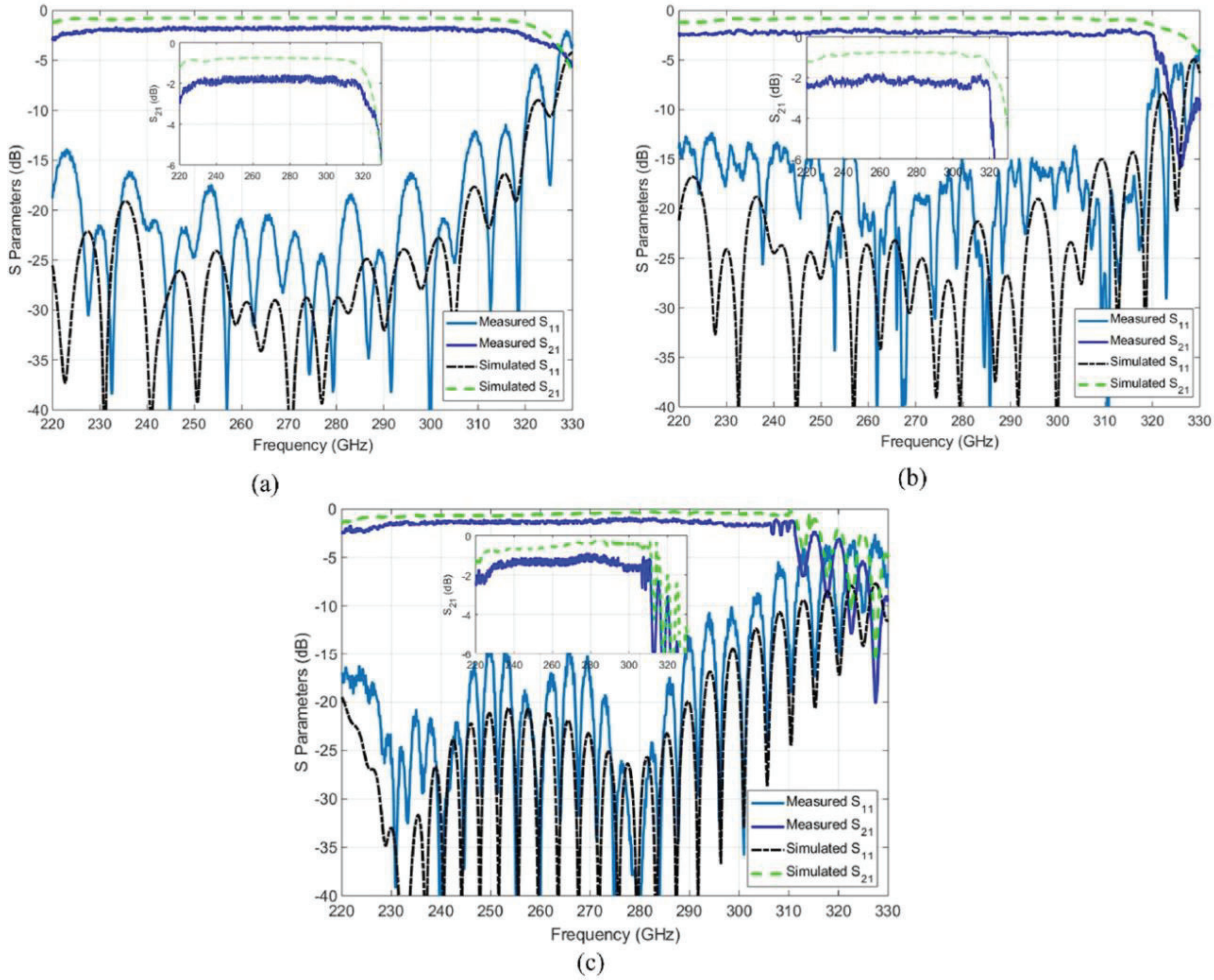

Figure 13: Measured (solid line) and simulated (dashed lines) S-parameters of the back-to-back (a) straight RGW transmission line, (b) bent RGW transmission line, (c) GGW transmission line.

<u>Conclusions and future work:</u>

Both the injection molding and SUEX dry film photoresist-based methods showed high fabrication accuracy and reproducibility for the manufacturing of 140 GHz slot array antennas, as well as suitability for batch fabrication of other passive waveguide THz components in a cost-efficient way.

The compatibility of the fabrication processes can be explored by fabricating more passive components. Both proposed fabrication methods are very simple to work with and are suitable for batch fabrication of WG components. Therefore, complicated geometries such as double-sided structures or multilayers can be attempted to explore the full potential of these fabrication methods. The integration of active and passive components merits further investigation. The CTEs of polymers are typically very different from those of metal and silicon, wherefore studies of thermal effects on integrating active components with polymer-based passive components will be required.

WP4 - Novel Packaging concept for integration of Radar chip with the gap waveguide based slot array

The main purpose of WP4 is to investigate highly-efficient integrating solutions for active circuits with gap waveguide antennas. Non-galvanic transitions between planar microstrip lines and gap waveguide transmission lines have been developed with low-loss characteristics, which subsequently have been utilized for the packaging of traditional MMICs. Detailed results are elaborated in journal paper [13] by Qiannan Ren et.al. The designs are suitable for the integration of MMICs with gap waveguide slot arrays. To further investigate highly-integrated radar front-ends, radar transceivers that provide waveguide interfaces with built-in planar transmission line to waveguide transitions have been developed. Detailed designs are explained in journal paper [14] by Qiannan Ren et.al. Finally, the validation of integration techniques based on non-galvanic microstrip-to-gap waveguide transitions has been successfully demonstrated in the realization of a polarimetric radar prototype. This achievement represents the collaborative efforts of WP2 and WP4. Detailed results are explained in journal paper [15] by Qiannan Ren, et.al.

<u>Summary of the integration techniques, related to Deliverable 4.1, 4.2 and 4.3</u>

With respect to the packaging of traditional MMICs operating at E-band, two microstrip to gap waveguide transitions have been developed. The transitions have been validated with back-to-back configurations as illustrated in Figure 14. The measurement agrees well with simulation, please see [13] for more information. Furthermore, the transitions have been verified by integrating off-the-shelf MMIC power amplifiers, as depicted in Figure. 15.

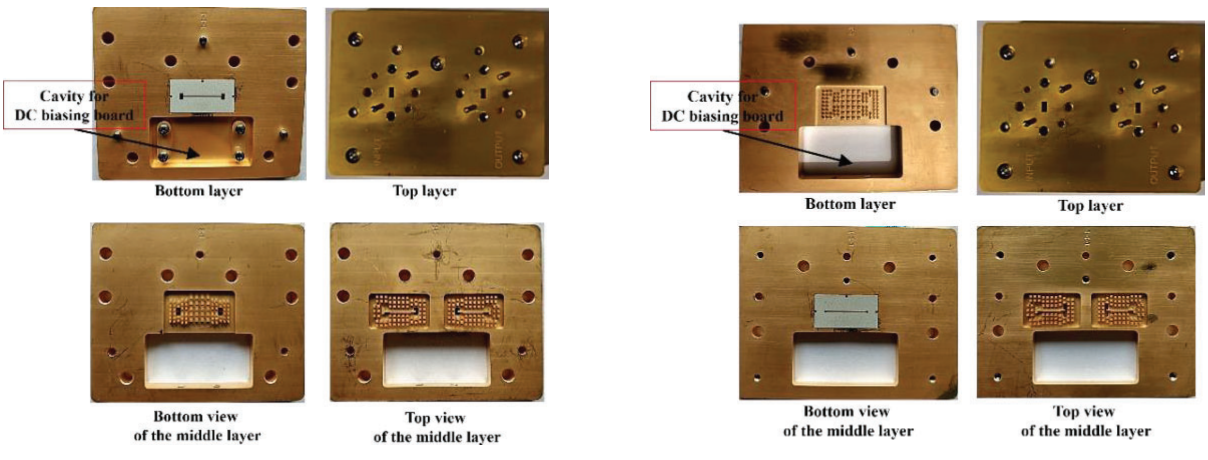

Figure 14. multi-layer display of the microstrip to gap waveguide transitions in back-to-back configuration.

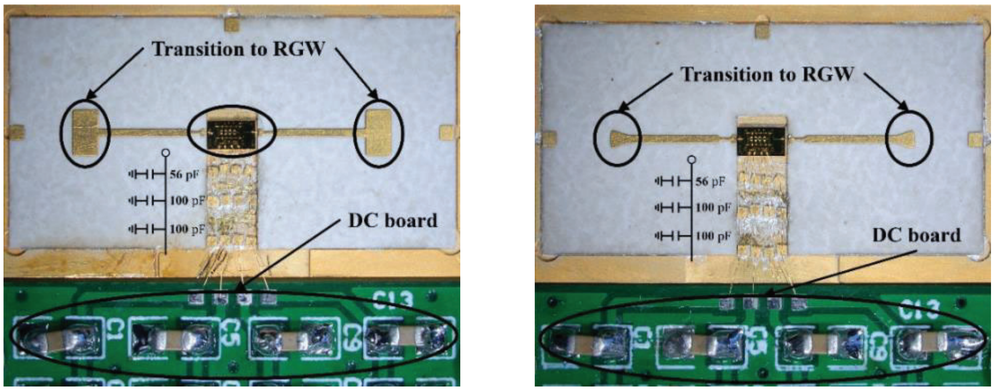

Figure 15. microstrip to gap waveguide transitions utilized in packaging of off-the-shelf MMICs.

State-of-the-art radar transceivers with launcher-in-package (LiP) technology have been explored for the integration of gap waveguide-based radar front-end. The transceivers are able to provide RF interfaces in the manner of waveguide ports, facilitating direct integration with waveguide antennas. Robust interconnects based on gap waveguide packaging techniques have been developed for the transceiver, as depicted in Figure 16. Please see [14] for more information.

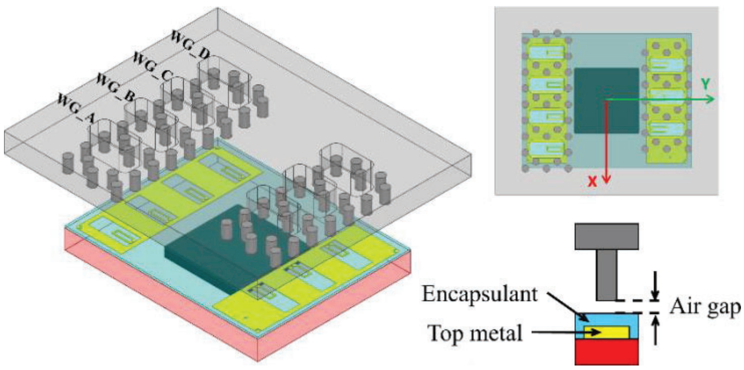

Figure 16. Compact gap waveguide interconnects for the LiP transceivers

The developed polarimetric radar prototype utilizes classic vertical transitions from microstrip to double ridge waveguides as depicted in Figure 17. The transitions are based on existing layout of the patches. The insertion losses of the transition have been explored by comparison with the reference radar, please see the details in [15].

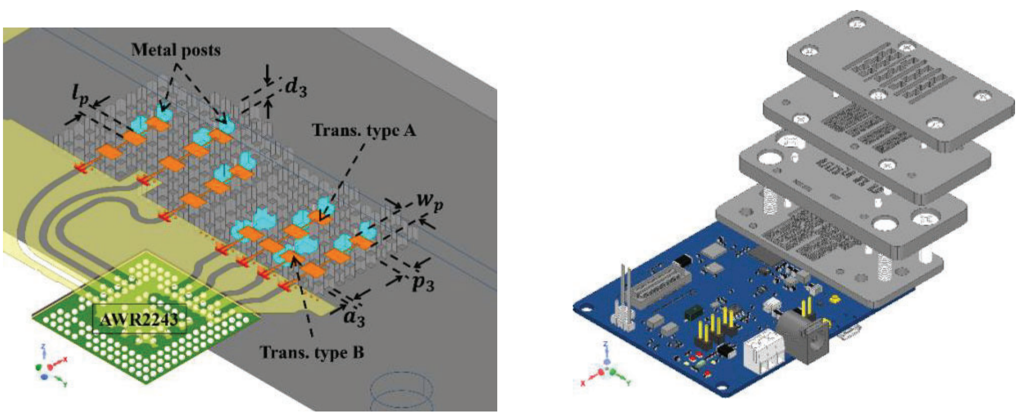

Figure 17. microstrip to waveguide transitions for the integration of radar transceivers with gap waveguide antenna.

Vertical transitions from microstrip lines to gap waveguides operating at 140 GHz band have been investigated as well. The transitions developed are using different matching techniques in order to explore the possibilities of wideband design. Moreover, the designs are implemented with back-to-back structure as depicted in Figure 18. The microstrips are fabricated employing various surface coatings to determine a cost-effective manufacturing with high performance. For more information, please refer to [16] by Anish Mishra.

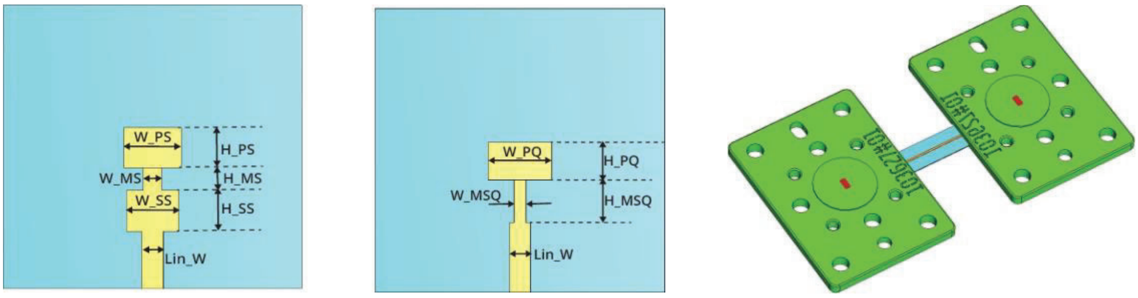

Figure 17. different matching techniques of the transition operating at 140 GHz

<u>*Conclusion and future work*</u>

The efforts that have been made in WP4 are focused on the integration of active circuits with gap waveguide components. The topic has been studied by firstly investigating the integration of traditional MMICs with ridge gap waveguides. Then, radar transceivers with launcher in package technology have been introduced to the development of integrated gap waveguide based radar front-end. Last but not least, the proposed integration techniques has been implemented in the polarimetric radar prototype that has been used in WP6. The design has been validated on system level with radar measurements in general.

WP5 - Polarization based sensing in automotive environment

The main of this WP was to build prototype of a sensor that can distinguish dry from wet and ice covered road surfaces. At earlier stage of the project we were focused on a passive radiometer that is measuring the combination of emitted and the reflected from the surface sky radiation. Based on the measurement at two orthogonal polarizations, the sensor is able to distinguish the surfaces since water and ice have substantially different dielectric constants. The sensor can potentially be used for road surface recognition in all weather conditions.

At a later stage of the project, we also developed a 77-81 GHz radar polarimetric sensor, which we believe is more attractive from commercial point of view for reasons that will be explained further in the report. The details of the work can be found in the following published work [17-22]

<u>**Passive polarimetric sensor, related to deliverable D5.1, 5.2 and D5.3**</u>

A surface can be characterized through its emissivity or reflectivity. Emissivity is a property of a surface to emit radiation. Both emissivity and reflectivity can take values between 0 and 1, high emissivity means low reflectivity and vice versa as emissivity+reflectivity=1. The effective emissivity of a surface depends on: dielectric constant of the media, surface roughness, thickness of the layers and the angle of incidence. Emissivity of a surface in wet and icy condition is expected to be different as water and ice have very different dielectric constants. The passive sensor characterizes the road condition by measuring the emissivity of the surface at two orthogonal polarizations between 82-98 GHz.

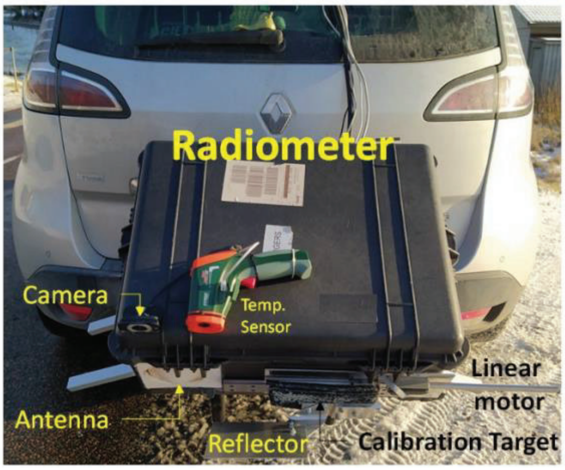

Figure 28 A picture of the radiometer mounted on a car for tests in winter conditions. The measurements were performed at the Veoneer test site at Vårgårda.

The road conditions presented in this report are dry asphalt, packed snow, unpacked snow, liquid water (a thin layer of liquid water sprayed over the surface), thick ice, and black (thin) ice, all shown in 19. In the same figure are depicted the measured emissivities for each of the groups. Irregularities and variations in the thicknesses cause the measured points to spread as "clouds". Yet, most of the surfaces are well distinguished.

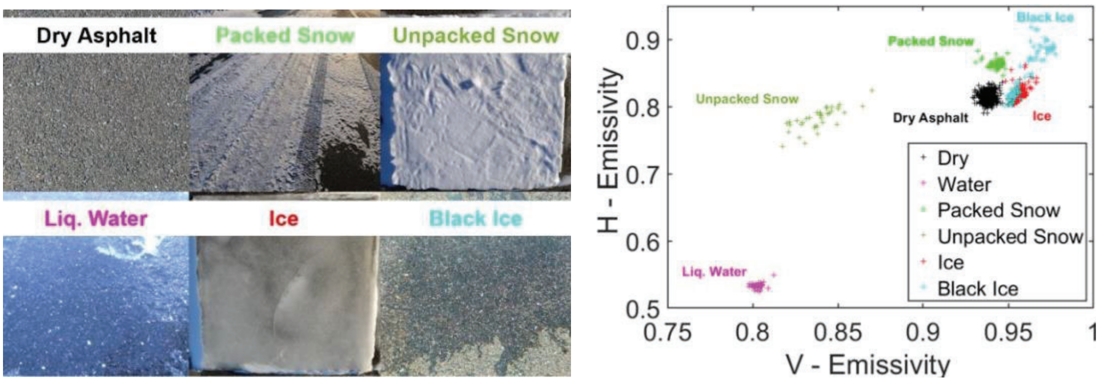

Figure 19 Six types of surfaces characterized by their emissivity for H and V polarizations

We found the passive method works well on surfaces that are uniform and do not change properties. For example, if the roughness of a dry asphalt change, the measured emissivity of a smoother asphalt can approach a region, which is typical for rougher, but icy surface. This fact represents an ambiguity in resolving some surfaces. To resolve such ambiguities additional information is needed. For example, knowledge of the surface roughness is very useful to minimize the "false alarms". The roughness can be measured but needs an additional radiometer channel, working at different frequency. This would increase the complexity of the sensor and make it less commercially attractive. Thus, we developed a second method based on a polarimetric active (radar) sensor, which is described in the following section.

Active polarimetric sensor

The method:

Even though asphalt can be a surface with uniform properties, it represents a random distributed target and can exhibit large variations from one illumination area to another (as in the case of a vehicle in motion). Therefore, a statistical approach is needed to extract useful information about the properties of the surface. Target entropy (TE) and auxiliary angle α are two polarimetric attributes, which are derived after several measurements of the polarimetric scattering matrix:

$$\begin{bmatrix} S_{VV} & S_{VH} \\ S_{HV} & S_{HH} \end{bmatrix}$$

Where the first index indicates the polarization of the transmitter and the second the polarization orientation of the receiver.

We use α-Entropy space, to characterize the surfaces. Entropy is a measure of the randomness of the scattering process and has a value of 0 for a single non-random target and 1 for a highly random distributed target where several scattering mechanisms are involved.

The mean polarimetric scattering angle α is one of the parameters defining the orientation of a polarization ellipse in the H/V plane. In the context of polarimetric measurements α indicates the dominant scattering mechanism as follows:

- $\alpha = 0^0$ surface scattering only
- $\alpha = 45^0$ dipole/volume scattering
- $\alpha = 90^0$ double bounce scattering

The sensor:

The radar sensor, shown in Figure 20, is based on AWR 1843 chipset from TI, it uses 2 transmitters and 2 receivers to measure the [S] scattering matrix. A picture of the polarimetric radar is shown in Figure . A conical horn antenna is followed by a waveguide polarization filter, which separate/combines the H and V components into orthogonal rectangular waveguides connected to the corresponding transmitter/receiver.

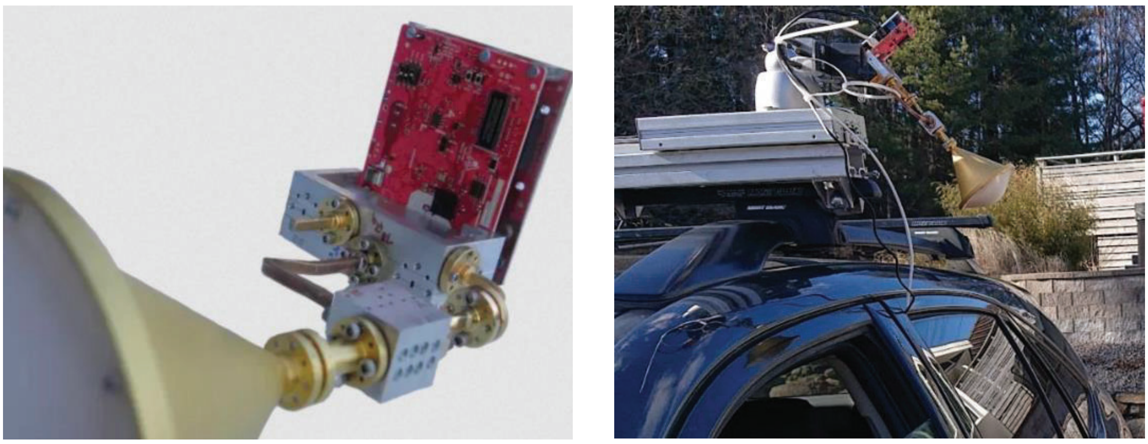

Figure 20 The 77-81 GHz polarimetric radar.

The radar is mounted on a vehicle and is looking sideways at a distance of about 2.3m from the surface, the entropy and α are then calculated for each range cell and averaged over the range where the surface is visible. An asphalt surface of normal roughness is measured in dry state and after spraying a thin layer of water. The result of this measurement is shown in Figure 2121.

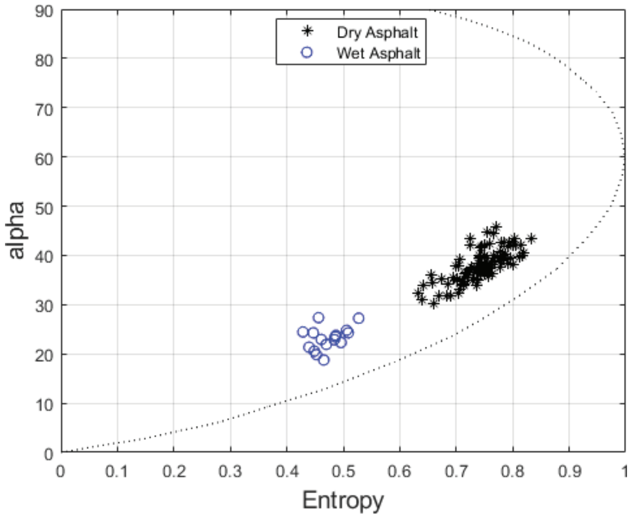

Figure 21 Asphalt of normal roughness in dry and wet condition. The dry surface is measured over a 99s interval, the wet surface patch is measured over 16s. It should be considered that α and entropy are not independant. The region of possible α values in the following figures is confined by the dotted lines.

Presence of a thin water-layer on the surface enhances the surface reflection, which makes the dominant surface scattering even stronger, resulting in reduced entropy and α value.
It can be seen from Figure 21 that the measured α-entropy values vary and form "clouds". These variations are associated with irregularities on the road surface, such as metal covers for water drainage, marking lines and patched holes on the road-surface. Examples of some of the irregularities are shown in Figure 2222.

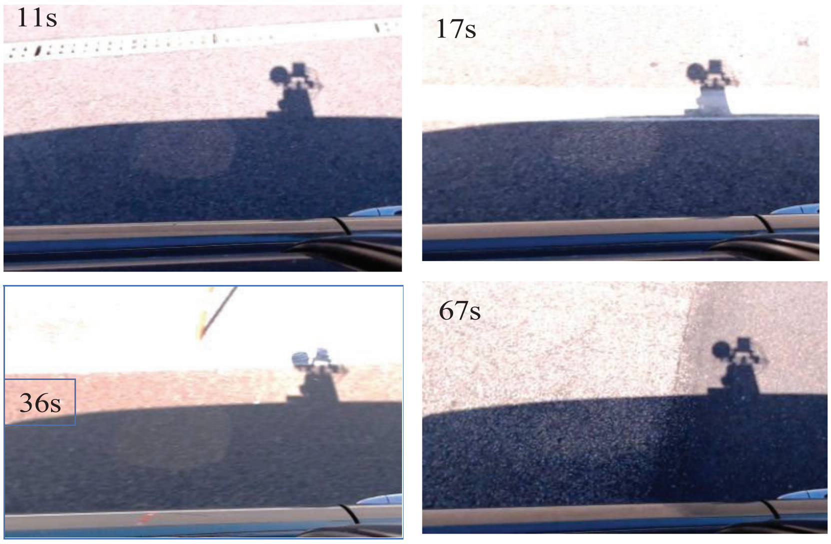

Figure 22 Examples of some of the irregularities responsible for the variations of the values of α-entropy: a metal cover, marking lines and patches.

In real measurement scenario these irregularities will exist, therefore in the following measurements they are not filtered resulting in spread of the values of the measured α and entropy. For the case of dry/wet surfaces from Figure 21, the clouds of points are sufficiently separated and therefore surfaces are identifiable.
The active sensor is also capable of distinguishing asphalt surfaces of different roughness. Measurements of 3 surfaces of different roughness are shown in Figure 23.

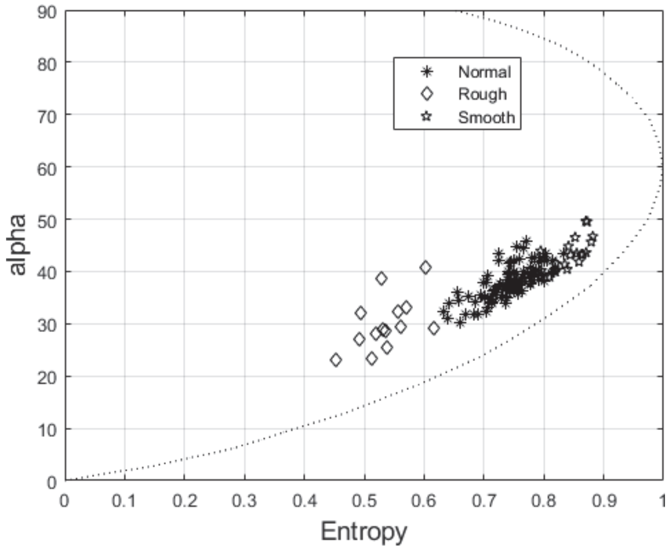

Figure 23 α, entropy plot for dry surfaces of different roughness. Normal: this is a surface with roughness, which is typical for the majority of public roads. We assume surface, RMS value ≈ 0.9mm. Rough: we do not know the value of roughness for this surface but we assume RMS of 3-6 mm. Smooth, that would be typical for new asphalt surface.

In another example, a section of pavement shown in Figure was measured and compared to asphalt. The pavement shows reduced entropy and α compared to the surrounding asphalt surface. The clouds of these 2 surfaces are well separated and identifiable with a good margin.

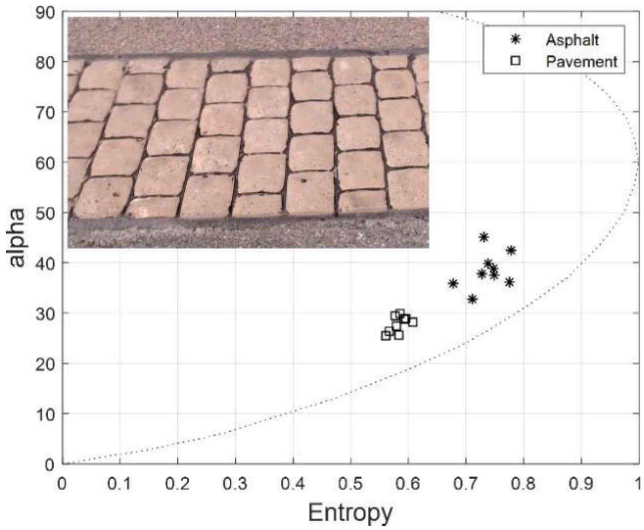

Figure 24 A patch of pavement embedded in asphalt of normal roughness.

Conclusions and future work

Two sensors for road-surface characterizations were developed in this WP5. The passive sensor is characterizing the surface through its emissivity in both H and V polarizations, using the measured combination of reflected “sky” and emitted from the surface radiation. The passive sensor requires knowledge of the sky and terrestrial temperatures. It also requires access to reflected “sky” radiation, which makes it difficult to use the passive-sensor in urban environment or tunnels, etc. To account for the fact that roughness of road surface varies, this sensor also requires additional input from external sensors in order to resolve possible ambiguities.

The active sensor is based on a statistical method for radar-image characterization developed in 1995 for SAR measurements. This method characterizes the road surface through its entropy and dominant scattering mechanism. The active sensor can discriminate ice from wet and dry surfaces. In addition, the active method can distinguish different type of surfaces, for example, rough or smooth surface from a surface with normal roughness. The active method is more robust than the passive and does not require knowledge of the sky/ground temperatures. It can be used in outdoor as well as in enclosed environment.

Two major measurement campaigns were carried out: the passive sensor was tested at the Veoneer test site at Vårgårda. The radar sensor was tested in 2023 at Volvo Cars test facility in Hällered. Some of the results of these campaigns are summarized in this report.

The goal of future work is to relate tire-friction to the polarimetric parameters measured ahead of the vehicle in real time and in motion. Ice and snow-covered road surfaces are of particular interest and in this project have been measured with the passive sensor. For the case of active sensor ice surfaces were measured only in laboratory conditions.

WP6 - Validation and Test drive

The main aim of the work package was to integrate the antenna/sensor developed in other work packages to collect measurement data to evaluate the developed sensors. The circular polarization antenna designed as part of WP2 was used to collect measurement data for validation purpose. The data collection activity involved collecting Radar measurement data at different environmental setting both in lab condition and test track condition. The method and results of data collection performed are described in the journal paper by Q. Ren [23]

Summary of the data collection related to Deliverable D 6.1 and D 6.2

The circular polarization antenna was assembled on the TI Radar board as shown in the figure below in figure 25.

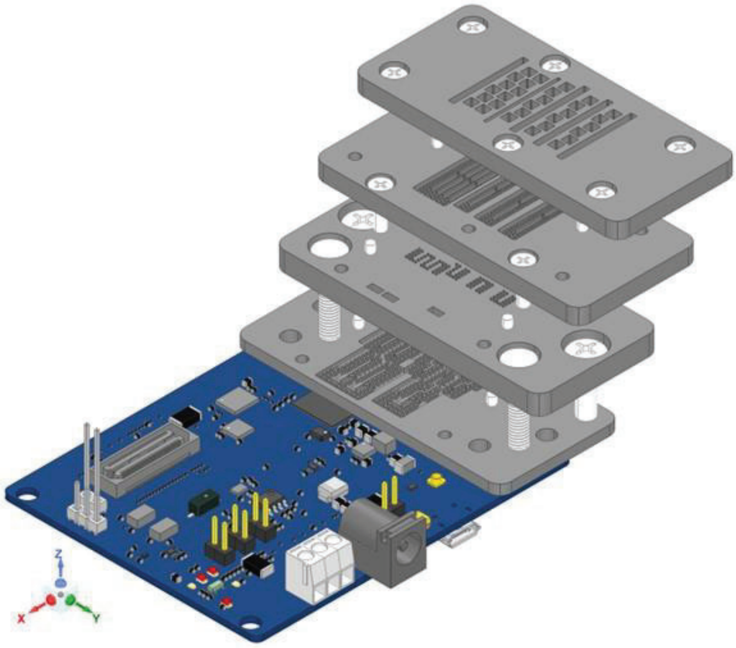

Figure 25 Illustration of polarimetric radar sensor used for data collection. [Qiannan paper]

Lab testing involved using Anechoic chamber at Chalmers with the use of corner reflectors. The test track testing involved, static measurement and dynamic measurement of different target objects. Three target objects were used - calibration pole, a car, and a cyclist with a dummy on top as is shown in figure 26.

Figure 26 Different objects used for measurement at the airfield.

The data collection setup for static measurement included remote-connected PC which controls the sensors and a GPS receiver. The measurement was conducted by a moving the setup in a pre-programmed circular path with the objects located at the center of the path using driver trolley. For the dynamic measurement the sensor setup with GPS receiver is mounted front of a test vehicle and driven by a test driver at specified speeds (figure 27). More details can be found in the paper [23]

Figure 27 Radar setup to carry out dynamic measurement.

The data collection effort resulted in 51 radar measurements in total for analysis. The combined analysis of data collected during both lab environment and test track is presented in the paper by Q.Ren [23].

Conclusion and future work

After evaluating data, it is clear that the polarimetric information does enable improved feature extraction. As expected from theory the more complicated road targets do have a more diverse return signal, see an example in figure 28.

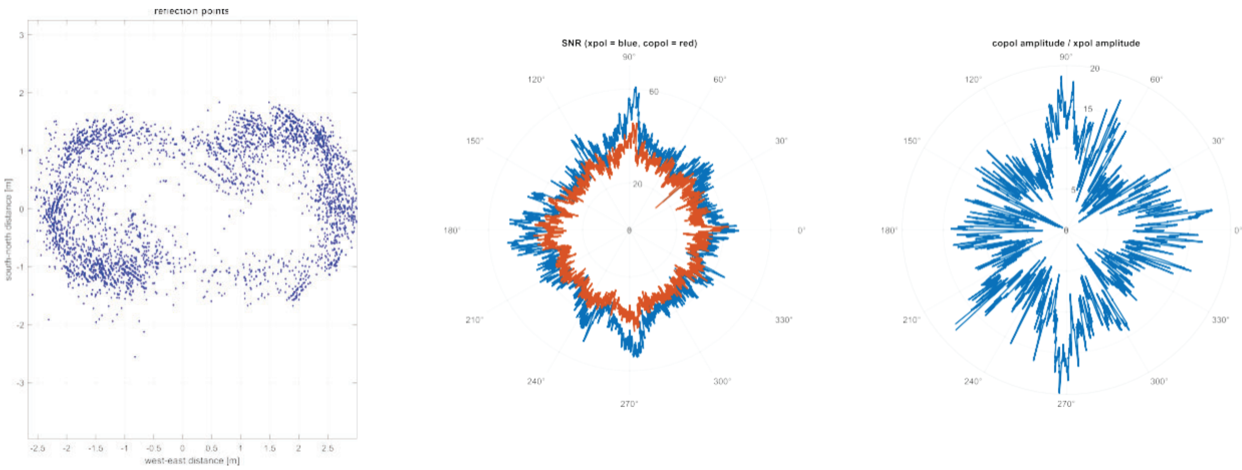

Figure 28 Data evaluation shows the detection point cloud, the SNR for both polarizations and the amplitude relationship between the two polarizations for all attitudes around the car.

The data also shows that the effects of multipath, ground reflections in this case, are reduced in the cross-polarization path which will produce a more consistent track of detections.

The limited number of RF channels in the radar polarimetric prototype does limit the angular resolution, which is indicated by the point cloud in figure 28 and this should be considered in the next step of the development.

Future work shall include additional data collection in more complex environments with much more multipath signals from other vehicles and infrastructure objects.

The polarimetric radar is definitely a possible solution for automotive radar which extends the RF information space.

7 Publications and spread of knowledge

Spread of Knowledge and Results

How are/are the project results planned to be used and disseminated?	Via academic publications, published journal papers and conference papers. Also, the results from the project has been presented in different conferences and workshops
Increase knowledge in the area	Yes, the project has produced scientific knowledge and results in the field of circular polarized antenna design, integration of multi-layer waveguide antenna and the radar electronics, radar antenna manufacturing techniques at 140GHz
Carried forward to other advanced technical development projects	The consortium is planning to apply for a next FFI project where more advanced development will be carried out to reach higher TRL levels.
Forwarded to product development	The results from this project are still early verification of new antenna concepts, new manufacturing techniques. More investigation is needed to carry forward this knowledge towards a product development
Introduction to market	Not yet
Used in regulations/standardization/political decision	Not yet

Publications

The project results have been disseminated through the following academic publications and conferences summarizing the concepts and experiences from prototyping and validation of different hardware modules for next generation automotive sensors. Also, the work has been summarized in three PhD dissertations, three technical Licentiate report and one MSc. Thesis report. The list of publications from this project are given below:

PhD thesis published and submitted:

[1] Sadia Farjana, PhD dissertation, Polymer-Based Micromachining for Scalable and CostEffective Fabrication of Gap Waveguide Devices Beyond 100 GHz, https://research.chalmers.se/publication/535595/file/535595_Fulltext.pdf

[2] Qiannan Ren, PhD dissertation, Advanced Automotive Radar Front-end: Based on Gapwaveguide Technology, will be published on 16th November, 2023.

[3] Zhaouri Zheng, PhD dissertation, Single layer Circular Polarized Antenna Array Suitable for Next Generation Automotive Radar Sensors, will be published on 22nd February, 2024.

Published Licentiate Thesis:

[1] Sadia Farjana, Licentiate Thesis, Polymer-Based Low-Cost Micromachining of Gap Waveguide Components, https://research.chalmers.se/publication/522791.

[2] Qiannan Ren, Licentiate Thesis , Towards an Advanced Automotive Radar Front-end Based on Gap Waveguide, https://research.chalmers.se/en/publication/537478.

[3] Zhaouri Zheng, Licentiate Thesis, Advanced Dual Circularly Polarized Antenna for Automotive Radar Systems, https://research.chalmers.se/en/publication/537479.

Published MSc. Thesis:

Mishra, Anish Ramkishan. "Microstrip-to-Waveguide transition for 140 GHz using Gap waveguide technology." M.S. thesis, Chalmers University of Technology, Gothenburg, 2021, https://odr.chalmers.se/items/354a68d6-8bbe-4a9b-a900-852465df3989

Published and Submitted Peer Reviewed Journal papers:

J.1 Z. Zang, A. U. Zaman and J. Yang, "Single Layer Dual Circularly Polarized Antenna Array Based on Ridge Gap Waveguide for 77 GHz Automotive Radar," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 7, pp. 5977-5982, July 2022, doi: 10.1109/TAP.2022.3161283.

J.2 Z. Zang, A. U. Zaman and J. Yang, "Single-Layer Dual-Circularly Polarized Series-Fed Gap Waveguide-Based Slot Array for a 77 GHz Automotive Radar," in IEEE Transactions on Antennas and Propagation, vol. 71, no. 5, pp. 3775-3784, May 2023, doi: 10.1109/TAP.2023.3243996.

J.3 S. Farjana et al., *Realizing a 140 GHz Gap Waveguide–Based Array Antenna by Low-Cost Injection Molding and Micromachining*, J Infrared Millimeter, and Terahertz Waves **42**, 893–914 (2021). https://doi.org/10.1007/s10762-021-00812-8.

J.4 S. Farjana et al., *Dry Film Photoresist-Based Microfabrication: A New Method to Fabricate Millimeter-Wave Waveguide Components*, Micromachines 2021, **12**, 260. https://doi.org/10.3390/mi12030260.

J.5 S. Farjana et al., *Low Loss Gap Waveguide Transmission line and Transitions at 220–320 GHz Using Dry Film Micromachining*, IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 11, no. 11, pp. 2012-2021, Nov. 2021, doi:10.1109/TCPMT.2021.3111137.

J.6 S. Farjana et al., *Micromachined Wideband Ridge Gap Waveguide Power Divider at 220–325 GHz*, IEEE Access, vol. 10, pp. 27432-27439, 2022, doi: 10.1109/ACCESS.2022.3156095.

J.7 S. Farjana et al., *Multilayer Dry Film Photoresist Fabrication of a Robust >100 GHz Gap Waveguide Slot Array Antenna*, IEEE Access, doi: 10.1109/ACCESS.2023.3271357

J.8 Q. Ren, A. U. Zaman, J. Yang, V. Vassilev, and C. Bencivenni, “Novel integration techniques for gap waveguides and MMICs suitable for multilayer waveguide applications,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 9, pp. 4120–4128, 2022.

J.9 Q. Ren, A. U. Zaman, and J. Yang, “Dual-circularly polarized array antenna based on gap waveguide utilizing double-grooved circular waveguide polarizer,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 11, pp. 10 436–10 444, 2022.

J.10 Q. Ren, C. Bencivenni, G. Carluccio, *et al.*, “Gapwaveguide automotive imaging radar antenna with launcher in package technology,” *IEEE Access*, vol. 11, pp. 37 483–37 493, 2023.

J.11 O. Auriacombe, V. Vassilev, N. Pinel, “Dual-Polarised Radiometer for Road Surface Characterisation”, *Journal of Infrared, Millimeter, and Terahertz Waves*, 43:108-124, March 2022.

J.12 V. Vassilev, “Road Surface Recognition at mm-Wavelengths Using a Polarimetric Radar”, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 23, 2022.

J.13 V. Vassilev, “Road surface characterization using a 77-81 GHz polarimetric radar”, submitted to *IEEE Transactions on Intelligent Transportation Systems.*

J.14 Q. Ren, O. Eriksson, P. Thalya, C. Bencivenni, M. Hasselblad, Jian Yang and A. Uz Zaman, ‘‘ An Automotive Polarimetric Radar Sensor with Circular Polarization Based on Gap waveguide Technology’’, *Submtted to IEEE Transactions on Microwave Theory and Technique*

Published Peer Reviewed International Conference and Workshop papers:

C.1 S. Farjana et al., *140 GHz Gap Waveguide Based Slot Array Antenna Fabrication Technique by Dry Film photoresist*, IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, July 23–28, 2023,Portland, Oregon, USA.

C.2 S. Farjana et al., *Micromachined Ridge Gap Waveguide Transmission Line and Transition at 220–310 GHz*, 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI), Singapore, Singapore, 2021, pp. 1297-1298, doi: 10.1109/APS/URSI47566.2021.9703735.

C.3 S. Farjana, et al., *Polymer based D-Band Multi-layer Gap Waveguide Slot Antenna Array for Line of Sight (LOS) MIMO Systems*, ICEAA-IEEE APWC 2020, Honolulu, Hawaii, USA, August 10-14, 2020.

C.4 O. Auriacombe; V. Vassilev; A. Uz Zaman, “Road Surface Characterization Using a Radiometer at 100 GHz”, *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz),* 2020

C.5 O. Auriacombe, V. Vassilev, “82 – 86 GHz Dual-polarised filterbank radiometer for road conditions monitoring”, *presented at 3rd URSI AT-AP-RASC*, June 2022.

C.6 Z. Zang, A. U. Zaman and J. Yang, "Design of Dual Circularly Polarized Inclined Slot Pair Based on Stepped-Height Ridge Gap Waveguide with Series Excitation," *2022 16th European Conference on Antennas and Propagation (EuCAP)*, Madrid, Spain, 2022, pp. 1-5, doi: 10.23919/EuCAP53622.2022.9768998.

C.7 Z. Zang, A. U. Zaman, J. Yang, C. Bencivenni and K. Konstantinidis, "Single Layer Dual Circularly Polarized Antenna Elements for Automotive Radar at 77 GHz," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, Dusseldorf, Germany, 2021, pp. 1-4, doi: 10.23919/EuCAP51087.2021.9411028.

C.8 Q. Ren, A. U. Zaman, J. Yang, V. Vassilev and C. Bencivenni, "Millimeter-Wave Vertical Transitions Between Ridge Gap Waveguides and Microstrip Lines for Integration of MMIC with Slot Array," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, Dusseldorf, Germany, 2021, pp. 1-4, doi: 10.23919/EuCAP51087.2021.9411273.

C.9 Q. Ren, A. U. Zaman and J. Yang, "A Dual Circularly Polarized Array Antenna for Ka-Band Satellite Communications," *2021 International Symposium on Antennas and Propagation (ISAP)*, Taipei, Taiwan, 2021, pp. 1-2, doi: 10.23919/ISAP47258.2021.9614491.

8 Conclusions and further research

a) More investigation on the circular polarized antenna based polarimetric radar sensor is needed to understand the full potential of the fully polarimetric radar sensor for automotive applications. Usually, the calibration process of the full polarimetric radar is quite complex and tedious. New simplified calibration technique needs to be developed to use the full potential of such sensors. Also, a mixed Circular/Linear Dual-Polarized Phased Array Concept for Automotive Radar at 77GHz can be of interest in this regard.

b) At 140GHz, only the antenna design is completed within this project. However, a fully functional 140GHz radar sensor needs to be developed to understand the performance improvement of the demonstrator compared to that of the 77GHz radar sensors.

c) The sensor for road surface characterization works quite well. However, the current sensor module is too bulky and take lots of space. To be useful for automotive applications, the complete sensor module needs to be more compact and low-profile. In the future work, the consortium plans to work in a collaborative way to make the road surface sensor more compact by using low-profile antenna arrays. Also another goal of future work is to relate tire-friction to the polarimetric parameters measured ahead of the vehicle in real time and in motion. Ice and snow-covered road surfaces are of particular interest and in this project have been measured with the passive sensor. For the case of active sensor ice surfaces were measured only in laboratory conditions.

d) Within this project, the goal was to work on hardware development for future automotive radar sensors. However, we see that new signal processing techniques need to be developed also to relax the calibration steps and to enable target detection from a complex set of data available from the newly developed radar. The consortium will work and collaborate with the signal processing experts in the field to enhance the performance of the developed sensors in the future project.

9 Participants and contact persons

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10 References

[1] Z. Zang, A. U. Zaman and J. Yang, "Single Layer Dual Circularly Polarized Antenna Array Based on Ridge Gap Waveguide for 77 GHz Automotive Radar," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 7, pp. 5977-5982, July 2022, doi: 10.1109/TAP.2022.3161283.

[2] Z. Zang, A. U. Zaman and J. Yang, "Single-Layer Dual-Circularly Polarized Series-Fed Gap Waveguide-Based Slot Array for a 77 GHz Automotive Radar," in IEEE Transactions on Antennas and Propagation, vol. 71, no. 5, pp. 3775-3784, May 2023, doi: 10.1109/TAP.2023.3243996.

[3] https://research.chalmers.se/publication/535595/file/535595_Fulltext.pdf

[4] S. Farjana et al., *Realizing a 140 GHz Gap Waveguide–Based Array Antenna by Low-Cost Injection Molding and Micromachining*, J Infrared Millimeter, and Terahertz Waves **42**, 893–914 (2021). https://doi.org/10.1007/s10762-021-00812-8.

[5] S. Farjana et al., *Dry Film Photoresist-Based Microfabrication: A New Method to Fabricate Millimeter-Wave Waveguide Components*, Micromachines 2021, **12**, 260. https://doi.org/10.3390/mi12030260.

[6] S. Farjana et al., *Low Loss Gap Waveguide Transmission line and Transitions at 220–320 GHz Using Dry Film Micromachining*, IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 11, no. 11, pp. 2012-2021, Nov. 2021, doi:10.1109/TCPMT.2021.3111137.

[7] S. Farjana et al., *Micromachined Wideband Ridge Gap Waveguide Power Divider at 220–325 GHz*, IEEE Access, vol. 10, pp. 27432-27439, 2022, doi: 10.1109/ACCESS.2022.3156095.

[8] S. Farjana et al., *Multilayer Dry Film Photoresist Fabrication of a Robust >100 GHz Gap Waveguide Slot Array Antenna*, IEEE Access, doi: 10.1109/ACCESS.2023.3271357.

[9] S. Farjana et al., *140 GHz Gap Waveguide Based Slot Array Antenna Fabrication Technique by Dry Film photoresist*, IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, July 23–28, 2023,Portland, Oregon, USA.

[10] S. Farjana et al., *140 GHz Gap Waveguide Based Slot Array Antenna Fabrication Technique by Dry Film photoresist*, IEEE International Symposium on Antennas and

Propagation and USNC-URSI Radio Science Meeting, July 23–28, 2023,Portland, Oregon, USA.

[11] S. Farjana et al., *Micromachined Ridge Gap Waveguide Transmission Line and Transition at 220–310 GHz*, 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI), Singapore, Singapore, 2021, pp. 1297-1298, doi: 10.1109/APS/URSI47566.2021.9703735.

[12] S. Farjana, et al., *Polymer based D-Band Multi-layer Gap Waveguide Slot Antenna Array for Line of Sight (LOS) MIMO Systems*, ICEAA-IEEE APWC 2020, Honolulu, Hawaii, USA, August 10-14, 2020.

[13] Q. Ren, A. U. Zaman, J. Yang, V. Vassilev, and C. Bencivenni, "Novel integration techniques for gap waveguides and MMICs suitable for multilayer waveguide applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 9, pp. 4120–4128, 2022.

[14] Q. Ren, A. U. Zaman, and J. Yang, "Dual-circularly polarized array antenna based on gap waveguide utilizing double-grooved circular waveguide polarizer," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 11, pp. 10 436–10 444, 2022.

[15] Q. Ren, C. Bencivenni, G. Carluccio, *et al.*, "Gapwaveguide automotive imaging radar antenna with launcher in package technology," *IEEE Access*, vol. 11, pp. 37 483–37 493, 2023.

[16] Mishra, Anish Ramkishan. "Microstrip-to-Waveguide transition for 140 GHz using Gap waveguide technology." M.S. thesis, Chalmers University of Technology, Gothenburg, 2021.

[17] O. Auriacombe; V. Vassilev; A. Uz Zaman, "Road Surface Characterization Using a Radiometer at 100 GHz", *International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz),* 2020

[18] O. Auriacombe, V. Vassilev, N. Pinel, "Dual-Polarised Radiometer for Road Surface Characterisation", *Journal of Infrared, Millimeter, and Terahertz Waves*, 43:108-124, March 2022.

[19] V. Vassilev, "Road Surface Recognition at mm-Wavelengths Using a Polarimetric Radar", *IEEE Transactions on Intelligent Transportation Systems*, Vol. 23, 2022.

[20] O. Auriacombe, V. Vassilev, "82 – 86 GHz Dual-polarised filterbank radiometer for road conditions monitoring", *presented at 3rd URSI AT-AP-RASC*, June 2022.

[21] O. Auriacombe, V. Vassilev, "Recognition of road surface conditions with a 82-98 GHz total power dual-polarized Radiometer on a Vehicle", submitted to *IEEE Transactions on Intelligent Transportation Systems.*

[22] V. Vassilev, "Road surface characterization using a 77-81 GHz polarimetric radar", submitted to *IEEE Transactions on Intelligent Transportation Systems.*

[23] Q. Ren, O. Eriksson, P. Thalya, C. Bencivenni, M. Hasselblad, Jian Yang and A. Uz Zaman, ‘‘ An Automotive Polarimetric Radar Sensor with Circular Polarization Based on Gap waveguide Technology’’, *Submtted to IEEE Transactions on Microwave Theory and Technique*